AD 742248

AD

USAAMRDL TECHNICAL REPORT 71-74

HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS

By

L. R. Burroughs

E. Stolper

R. Hawkins

February 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-70-C-0040
SIKORSKY AIRCRAFT
DIVISION OF UNITED AIRCRAFT CORPORATION
STRATFORD, CONNECTICUT

Approved for public release;
distribution unlimited.

U.S. ARMY MATERIEL COMMAND

DISCLAIMERS

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission, to manufacture, use, or sell any patented invention that may in any way be related thereto.

Trade names cited in this report do not constitute an officail endorsement or approval of the use of such commercial hardware or software.

DISPOSITION INSTRUCTIONS

Destroy this report when no longer needed. Do not return it to the originator.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Sikorsky Aircraft Division of United Aircraft Corporation Stratford, Connecticut	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Lester R. Burroughs
Edwin Stolper
Richard Hawkins

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1972	246	1

8a. CONTRACT OR GRANT NO. DAAJ02-70-C-0040 b. PROJECT NO. TASK 1F162203A14301 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAMRDL Technical Report 71-74 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) Sikorsky Engineering Report 50710

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Eustis Directorate U.S. Army Air Mobility R&D Laboratory Fort Eustis, Virginia

13. ABSTRACT

This project was conducted to study the relationships between various component reliability objectives and the test requirements necessary to achieve those objectives. Several test techniques and combinations of tests have been evaluated during this program to provide a basis for a more meaningful test program for the development phase of a helicopter program.

The H-3 series helicopter program has been used to provide a basis for the trade-off studies. The test and service experience has been reviewed to provide a data bank on the performance of transmission and rotor system components and to determine modes and types of failures. The extent of correlation between failures during the initial test programs and those problem areas that were later detected during actual usage was investigated to determine the effectiveness of the test programs.

Several changes have been advocated in both testing philosophy and the corresponding test techniques since the H-3 helicopter test program commenced. Various testing concepts have been considered and compared to develop a recommended test program for a single-rotor helicopter having a nominal gross weight of 15,000 pounds. This program allows for identification of problem areas, subsequent modification of the components as required, and qualification of the modified components with a high degree of confidence that the design objectives will be demonstrated and achieved.

The recommended test approach has suggested various modifications to the corresponding design and test specifications. The proposed revisions to these specifications are also included in this report.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Reliability						
Demonstration testing						
Development Testing						
Component testing						

Unclassified
Security Classification

1662-72

DEPARTMENT OF THE ARMY
U. S. ARMY AIR MOBILITY RESEARCH & DEVELOPMENT LABORATORY
EUSTIS DIRECTORATE
FORT EUSTIS, VIRGINIA 23604

This report was prepared by the Sikorsky Aircraft Division of United Aircraft Corporation under the terms of Contract DAAJ02-70-C-0040. It presents the results of a study to establish the relationships between various reliability demonstration objectives and the test requirements (type, hours, components required, cost, etc.) necessary to achieve those objectives.

The objective of this contractual effort was to perform historical data review and analysis and cost and effectiveness trade-offs necessary to identify reliability testing requirements that are applicable during new helicopter system development programs.

In general, it can be stated that the sample and recommended helicopter development reliability test programs presented in this report are a possible approach to a helicopter dynamic components development effort.

In the use of this report, attention is directed to the test hours relationships extrapolated from the data review and analysis effort together with the test program trade-off studies performed. Because of the nature of this study and the limitations of the data available, the contractor was required to rely heavily on engineering judgment.

The conclusions and recommendations contained herein are concurred in by this Directorate. The concurrence is based on acceptance of the data reviewed and assumptions made in performing the analysis and trade-off studies leading to the development of the sample test plans together with the program approach for future helicopter programs.

The technical monitor for this contract was Mr. Thomas E. Condon of the Reliability and Maintainability Division of this Directorate.

Task 1F162203A14301
Contract DAAJ02-70-C-0040
USAAMRDL Technical Report 71-74
February 1972

HELICOPTER DEVELOPMENT RELIABILITY TEST REQUIREMENTS

Final Report

By

L.R. Burroughs
E. Stolper
R. Hawkins

Prepared by

Sikorsky Aircraft
Division of United Aircraft Corporation
Stratford, Connecticut

for

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

SUMMARY

This project was conducted to study the relationships between various component reliability objectives and the test requirements necessary to achieve those objectives. Several test techniques and combinations of tests have been evaluated during this program to provide a basis for a more meaningful test program for the development phase of a helicopter program.

The H-3 series helicopter program has been used to provide a basis for the trade-off studies. The test and service experience has been reviewed to provide a data bank on the performance of transmission and rotor system components and to determine modes and types of failures. The extent of correlation between failures during the initial test programs and those problem areas that were later detected during actual usage was investigated to determine the effectiveness of the test programs.

Several changes have been advocated in both testing philosophy and the corresponding test techniques since the H-3 helicopter test program commenced. Various testing concepts have been considered and compared to develop a recommended test program for a single-rotor helicopter having a nominal gross weight of 15,000 pounds. This program allows for identification of problem areas, subsequent modification of the components as required, and qualification of the modified components with a high degree of confidence that the design objectives will be demonstrated and achieved.

The recommended test approach has suggested various modifications to the corresponding design and test specifications. The proposed revisions to these specifications are also included in this report.

FOREWORD

This report presents a recommended test program to reasonably demonstrate specified reliability objectives for the transmission and rotor system components of a single-rotor helicopter. Test and service data on the H-3 series helicopter is used to lend support to the suggested approach used in the test program. The design parameters considered in this study were outlined in Contract DAAJ02-70-C-0040 (DA Task 1F162203A14301). Sikorsky Aircraft, a Division of United Aircraft Corporation, was the contractor for this study.

The program was conducted at Sikorsky Aircraft under the technical direction of Mr. Lester R. Burroughs, Supervisor, Transmission Design and Development. Principal investigators for this program were Mr. James Lastine, Mr. Edwin Stolper, and Mr. Richard Hawkins. Meaningful technical contributions were made by Mr. Joseph Pratt and Mr. John Longobardi; USAAMRDL technical direction was provided by Mr. Thomas House and Mr. Thomas Condon.

TABLE OF CONTENTS

	Page
SUMMARY	v
LIST OF ILLUSTRATIONS	xi
LIST OF TABLES	xviii
LIST OF ABBREVIATIONS	xix
INTRODUCTION	1
EXPERIENCE WITH THE H-3 HELICOPTER	3
GENERAL DESCRIPTION OF H-3 SERIES HELICOPTER	3
Description of Transmission System	3
Description of Main Rotor System	13
Description of Antitorque Rotor System	22
DESCRIPTION OF TRANSMISSION SYSTEM TEST PROGRAM	31
RESULTS OF TRANSMISSION SYSTEM TESTING	32
Main Gearbox	32
Intermediate and Tail Gearboxes	41
DESCRIPTION OF ROTOR SYSTEM TEST PROGRAM	41
RESULTS OF ROTOR SYSTEM TESTING	44
Main Rotor System	44
Tail Rotor System	46
SERVICE EXPERIENCE	48
SERVICE EXPERIENCE WITH H-3 TRANSMISSION SYSTEM	48
COMPARISON OF TRANSMISSION SYSTEM TEST AND SERVICE EXPERIENCE	50
SERVICE EXPERIENCE WITH H-3 ROTOR SYSTEM	55
COMPARISON OF ROTOR SYSTEM TEST AND SERVICE EXPERIENCE	56
EFFECTIVENESS OF TESTING	64

Page

Transmission System 64

Rotor System 65

INVESTIGATION OF OTHER TEST TECHNIQUES 68

SUGGESTED APPLICATIONS OF VARIOUS TEST TECHNIQUES 71

TEST PROGRAM TRADE-OFF STUDIES 74

INTRODUCTION 74

TYPES OF TEST 74

Fatigue Tests 74

Systems Test 75

Development and Demonstration Testing 75

TEST PLANS 76

Test Duration 76

Component Requirements 78

Program Cost 78

PROGRAM FLEXIBILITY 78

EFFECT OF VARYING LEVELS OF RELIABILITY 99

Demonstration Test Program 99

Development Test Program 102

Cost and Duration of Program 104

Effects of Acceleration 105

SAMPLE TEST PROGRAM 120

INTRODUCTION 120

PROTOTYPE AND DESIGN SELECTION TESTS 120

BEARING AND SEAL TESTS 123

TRANSMISSION SPECIAL COMPONENT BENCH TESTS 123

TRANSMISSION SYSTEM TESTS 123

ROTOR AND CONTROLS STRUCTURAL
COMPONENTS TESTS 126

Page

MAIN ROTOR AND TAIL ROTOR WHIRL TESTS 131

PROPULSION SYSTEM TEST BED 134

TIEDOWN TEST 134

FLIGHT TEST 137

SUMMARY 137

RECOMMENDED TEST PLAN 141

INTRODUCTION 141

DISCUSSION 141

Transmission Bench Test 142

Rotor Head Bench Test 145

Propulsion System/Tiedown Test 145

Aircraft Flight Test 146

Follow-on Product Improvement Tests 146

SUMMARY 147

COMMENTS ON APPLICABLE MILITARY SPECIFICATIONS 148

MIL-A-8064B (USAF); ACTUATORS AND ACTUATING SYSTEMS AIRCRAFT, ELECTROMECHANICAL, GENERAL REQUIREMENTS 148

MIL-C-5503C; CYLINDERS: AERONAUTICAL, HYDRAULIC ACTUATING GENERAL REQUIREMENTS FOR 148

MIL-D-23222; DEMONSTRATION REQUIREMENTS FOR ROTARY WING AIRCRAFT 148

MIL-T-5955C: TRANSMISSION SYSTEMS, VTOL-STOL, GENERAL REQUIREMENTS FOR 148

MIL-T-8679; TEST REQUIREMENTS, GROUND, HELICOPTER 148

MIL-H-8775C; HYDRAULIC SYSTEM COMPONENTS, AIRCRAFT AND MISSILES 149

CONCLUSIONS 150

	Page
APPENDIXES	151
I. SUPPLEMENTARY DATA TO TEST PROGRAM TRADE-OFF STUDIES	151
II. THE FAILURE RATE ANALYSIS PROGRAM	176
III. H-3 DEVELOPMENT PROGRAM, FAILURE SUMMARY	209
DISTRIBUTION	228

LIST OF ILLUSTRATIONS

Figure		Page
1	H-3 Series Helicopters	4
2	H-3 Rotor and Transmission System	5
3	Input Section, Main Gearbox	7
4	Main Gearbox, Section View	9
5	H-3 Main Gearbox	11
6	Intermediate Gearbox	15
7	Tail Gearbox	17
8	Main Rotor Head With Blade Fold	19
9	Plan View, H-3 Oil Lubricated Main Rotor Head	20
10	Side View, H-3 Oil Lubricated Main Rotor Head	21
11	Main Rotor Head, Section View	23
12	Swashplate Assembly	25
13	Details of Main Rotor Blade Assembly	27
14	Details of Tail Rotor Assembly	29
15	Tail Rotor Bearing Arrangement	30
16	Tail Rotor Blade Assembly	30
17	H-3 Program Schedule	33
18	H-3 Main Gearbox Malfunctions by Category	35
19	H-3 Main Gearbox Design Modifications During Testing	36
20	H-3 Main Geartox Failures, Propulsion System Test Bed	38
21	H-3 Main Gearbox Failures, Tiedown Aircraft	38
22	H-3 Main Gearbox Failures, Regenerative Test Stand	39

Figure		Page
23	H-3 Main Gearbox Failures, All Test Programs	42
24	H-3 Tail and Intermediate Gearbox, Regenerative Test Stand	43
25	H-3 Main Rotor Failures, Propulsion System Test Bed	44
26	H-3 Main Rotor Failures, Tiedown Test Facility	45
27	H-3 Main Rotor Failures, 8000-Horsepower Whirl Stand	45
28	H-3 Main Rotor Head Component Failures, All Test Programs (Excluding Laboratory Fatigue Test Programs)	46
29	H-3 Tail Rotor Failures, All Test Programs (Excluding Laboratory Fatigue Test Programs)	46
30	2000-Horsepower Tail Rotor Test Facility	47
31	H-3 Main Gearbox Service Failures	49
32	H-3 Intermediate Gearbox Service Failures	51
33	H-3 Tail Gearbox Service Failures	52
34	H-3 Main Gearbox, Comparison of Service and Test Failures	53
35	H-3 Main Gearbox, Miscellaneous Service Failures	55
36	Effectiveness of Development Testing	66
37	Typical Work Breakdown Structure	77
38	Plan 1, Selected Test Program	83
39	Plan 1, Selected Test Program Flow Chart	85
40	Concurrent Test Schedule	87
41	Sequential Test Schedule	88
42	Cumulative Cost Versus Time at 500-Hour MTBR at 60 Percent Confidence Level	89

Figure		Page

Figure		Page
43	Main Transmission Regenerative Bench Testing Hours Versus Cost	90
44	Main Rotor Whirl Testing Hours Versus Cost	90
45	Effect of Environmental Duplication on the Probability of Detecting New Modes of Failure	91
46	Change Cost as the Sum of Related Costs	93
47	Program Cost Risk as the Product of Cost To Fix,and Probability of Detecting a Mode of Failure	94
48	Effect of Prototype Development on Probability of Detecting a Mode of Failure	95
49	Statistical Nature of the Value of MTBR	95
50	Lack of Interaction of MTBF With Test Program Constraints	97
51	Effect of Cost on the Time Required To Obtain an Estimate of MTBF	97
52	Effect of Time on Cost Required To Obtain an Estimate of MTBF	98
53	Interrelationship of Cost and Time for a Particular Test Plan	98
54	Variation in Cost/Time Relationship Between Plans	100
55	MTBR Versus MTBF for Constant TBO's	107
56	Test Hours Versus Maximum Allowable Failures	109
57	Plot of Percentage of Increase in MTBF Versus Development Test Duration	111
58	Plot of Percentage of Increase in MTBF Versus Development Test Duration for Various Level of Testing	112
59	Various Components MTBF Versus Development Hours	113
60	Component MTBF Versus Development Hours	114

Figure		Page
61	Demonstration Test Hours Versus Required Component Time MTBF	115
62	Cost Versus Time at 500-Hour MTBR	116
63	Cost Versus Time at 1000-Hour MTBR	117
64	Cost Versus Time at 1500-Hour MTBR	118
65	Load/Life Relationship	119
66	Sample Test Plan Schedule	121
67	H-3 Main Gearbox Regenerative Test Stand	125
68	Structural Reliability Fatigue Laboratory Shaker Tables	127
69	Structural Reliability Fatigue Laboratory	128
70	H-3 Fatigue Test of Main Rotor Inboard Spar Section	129
71	H-3 Main Rotor Head and Shaft Fatigue Test Facility	130
72	Effect of Mode of Failure Tests on Development	132
73	8000-Horsepower Main Rotor Whirl Stand	133
74	H-54 Propulsion System Test Bed	135
75	H-3 Tiedown Aircraft	136
76	Recommended Test Plan Schedule	143
77	Plan 2, Test Plan	153
78	Plan 2, Flow Chart	155
79	Plan 2, Concurrent Schedule	157
80	Plan 3, Test Plan	159
81	Plan 3, Flow Chart	161
82	Plan 3, Concurrent Schedule	163
83	Plan 4, Test Plan	165

Figure		Page
84	Plan 4, Flow Chart	167
85	Plan 4, Concurrent Schedule	169
86	FRAP Failure Versus TSO Plot	177
87	Failure Rate Plot	178
88	FRAP Survival Plot	179
89	FRAP Failure Versus TSO: CH-3C/HH-3E Intermediate Gearbox	181
90	FRAP Failure Versus TSO: CH-3C/HH-3E .... Intermediate Gearbox	183
91	FRAP Failure Versus TSO: CH-3C/HH-3E Intermediate Gearbox	184
92	FRAP Failure Rate: CH-3C/HH-3E Intermediate Gearbox	185
93	FRAP Survival Plot: CH-3C/HH-3E Intermediate Gearbox	186
94	FRAP Failure Rate: CH-3C/HH-3E Intermediate Gearbox	187
95	FRAP Survival Plot: CH-3C/HH-3E Intermediate Gearbox	188
96	FRAP Failure Versus TSO: CH-3C/HH-3E Tail Gearbox	189
97	FRAP Failure Rate: CH-3C/HH-3E Tail Gearbox	191
98	FRAP Survival Plot: CH-3C/HH-3E Tail Gearbox	192
99	Failure Versus TSO: CH-3C/HH-3E Main Rotor Head	193
100	Failure Versus TSO: CH-3C/HH-3E Main Rotor Head	194
101	Failure Versus TSO: CH-3C/HH-3E Main Rotor Head	194

Figure		Page

102 Failure Versus TSO: CH-3C/HH-3E Main Rotor Head 195

103 Failure Versus TSO: CH-3C/HH-3E Main Rotor Head 195

104 Failure Versus TSO: CH-3C/HH-3E Main Rotor Head 196

105 Failure Versus TSO: CH-3C/HH-3E Main Rotor Head 196

106 Failure Versus TSO: CH-3C/HH-3E Main Rotor Head 197

107 Failure Versus TSO: CH-3C/HH-3E Main Rotor Head 197

108 FRAP Failure Rate: CH-3C/HH-3E Main Rotor Head 199

109 FRAP Survival Plot: CH-3C/HH-3E Main Rotor Head 200

110 FRAP Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 201

111 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 202

112 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 202

113 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 204

114 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 204

115 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 205

116 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 205

117 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 206

118 Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head 206

Figure		Page

119 FRAP Failure Rate Plot: CH-3C/HH-3E Tail Rotor Head 207

120 Survival Plot: CH-3C/HH-3E Tail Rotor Head 208

LIST OF TABLES

Table		Page
I	Major Differences, H-3/S-61 Rotor Systems	12
II	Comparative Data, H-3 Main Gearbox Test Stands	37
III	Mode of Failure Summary, H-3 Main Gearbox	40
IV	Comparative Failure Data	50
V	H-3 Field Service Rotor Blade Failure Removal Data	57
VI	H-3 Field Service Main Rotor Head Removal Data	59
VII	H-3 Field Service Tail Rotor Head Removal Data	61
VIII	Mode of Failure Data, H-3 Rotor System Field Service	63
IX	Failures Related to Various Subassemblies	65
X	Type of Tests and Their Applicability	68
XI	Test Duration, Component Requirements 500-Hour, 60-Percent Confidence Test Plan	79
XII	Test Costs	81
XIII	Trade-Off Study Factors	96
XIV	Aircraft Design Parameters	137
XV	Summary of Sample Test Program	139
XVI	Component Requirements for the Four Test Plans	152
XVII	Reliability Predictions Using the Four Test Plans	170
XVIII	Reliability Definitions Using the Four Test Plans	171
XIX	H-3 Development Program Failure Summary	210

LIST OF ABBREVIATIONS

APU	auxiliary power unit
ECP	engineering change proposal
FRAP	failure rate analysis program
MTBF	mean time between failures
MTBR	mean time between removals
P/N	part number
S/N	serial number
TBO	time between overhauls
TSO	time since overhaul

INTRODUCTION

There is sufficient amount of historical data available to indicate that the reliability of helicopter dynamic components could be significantly improved by the adoption of adequate and timely development test programs. These programs properly implemented would include not only testing but component development and design improvements. In this manner, increased component mean time between removals (MTBR's) and better aircraft availability in operational service will result. Since low reliability results in large logistic and maintainability expenditures, it appears that more extensive development testing would be cost effective, not only in decreasing spares requirements but also in increasing aircraft availability early in its operational phase, thereby reducing the overall life cycle costs of helicopter systems.

Low MTBR values are the direct result of premature removals in combination with the forced removal of the good components at their prescribed time between overhaul (TBO). These unnecessary removals that are the direct result of designated overhaul intervals cause good components to be removed from service. These components with excellent service experience could offset the adverse effects of premature removals, were they not forced into the overhaul cycle. However, as long as components have prescribed TBO values, the only way the MTBR can approach the TBO is to reduce the number of premature failures through more timely and effective testing and initiation of corrective action in the initial development phase.

While some helicopter programs include both development and qualification testing, funded testing usually includes only qualification testing. While the qualification testing is conducted in accordance with test requirements outlined in prescribed specifications, the only development testing that is conducted is usually proposed by the contractor and approved by the procuring activity. Minimum program costs are usually obtained by eliminating all unnecessary costs, which usually curtails the extent of any test program including development testing.

Marked reductions in premature removals and excessive maintenance costs can be obtained if proper consideration is given to reliability during the initial design and test phases of the helicopter program. The initial development and qualification test program can be structured to debug and develop aircraft components and provide an indication of the inherent component reliability as well. Meaningful development testing capable of demonstrating reliability objectives is often an elusive goal, both from a financial and an engineering viewpoint. Reliability demonstration requires a mean time between failure (MTBF) design objective well above the level to be demonstrated. The margin varies with the test program the customer can afford, the risk the customer is willing to take that he may accept defective equipment, and the risk the producer is willing to take that he may fail the demonstration.

To determine the relationship and relative effectiveness of past test programs, this report examines the test and service experience on the

transmission and rotor systems of the Sikorsky Aircraft H-3 series helicopter. A description of these systems is presented together with a history of test and service failure data as well as an analysis of the relative effectiveness of each test procedure used.

Various test plans are considered and from these a test plan is selected for trade-off studies, one of concurrent and sequential test arrangements with a statistical analysis of the required number of test specimens and test duration, the other which evaluates the impact of development and demonstration testing on cost at levels of reliability of 500, 1000, and 1500 hours MTBR in combination with confidence levels of 30, 60, and 90 percent. A sample plan which is essentially the selected sequential test plan is then described in further detail. Finally, a recommended test plan is presented. This plan emphasizes accelerated development testing, which is a key to achieving a higher level of reliability early in a program. The recommended test program is proposed for consideration in preparing future specifications for helicopter dynamic system procurement.

As a result of this study, effort guidelines for planning future helicopter development and reliability demonstration programs are presented.

EXPERIENCE WITH THE H-3 HELICOPTER

GENERAL DESCRIPTION OF H-3 SERIES HELICOPTERS

The H-3 series helicopter, with a commercial model designation of S-61, was designed for an antisubmarine warfare mission. This single-rotor helicopter, with a gross weight of 17,000 pounds, commenced as a turbine-powered growth version of the H-34 helicopter.

This series of helicopters has been developed for many different applications; several configurations are shown in Figure 1. These aircraft have seen extensive service with domestic and foreign military and civilian operators, as indicated by the more than 1,125,000 flight hours accumulated thus far. The SH-3D is an improved growth version of the original SH-3A aircraft. The S-61L is a stretched commercial version of the same aircraft, essentially using the same drive train and rotor system components. The HH-3C is in use with the U.S. Air Force and features mid-air refueling capability for extended-range search and rescue missions. This aircraft utilizes a new fuselage providing a rear loading ramp, an increase in load-carrying capability, and a 22,000-pound gross weight. The drive train has been modified to accept accessory power from an auxiliary power unit for ground operation of all accessories without using the primary turbines. The VH-3A is an executive version of the SH-3A aircraft. The rotor and transmission systems are similar for both aircraft except that the VH-3A has a remote auxiliary power unit (APU) mounted in one sponson, for ground operation of selected accessories and air conditioning. The two T-58 turbine engines supply power directly to the main gearbox, which is the nucleus of the drive train. The main gearbox supplies power to the tail rotor drive system and to the accessories which are mounted directly on the main gearbox, as well. Power is supplied to the semiarticulated tail rotor by two speed reducing angle gearboxes and the connecting drive shafting. The basic rotor and transmission systems are shown in Figure 2.

The rotor system for the aforementioned aircraft consists of a main rotor and an antitorque tail rotor. The main rotor head commenced as a grease-lubricated assembly but has been changed to an oil-lubricated assembly for several models, as can be seen from Table I. Automatic blade fold is also present on all U.S. Navy main rotor head assemblies. The semiarticulated tail rotor has also experienced similar changes as noted.

Description of Transmission System

The H-3 transmission system accepts power from two T-58 turbine engines having an output speed of 18,966 rpm, and supplies power to the main rotor rotating at 203 rpm, the tail rotor rotating at 1,243 rpm, and several accessories mounted on the main gearbox. As shown in Figure 2, three gearboxes are used in this aircraft. Two relatively simple bevel gearboxes are used in the tail rotor drive train, while the main gearbox is considerably more complex, as shown in Figures 3, 4, and 5.

The main gearbox shown in these figures incorporates an input spur gear

VH-3A

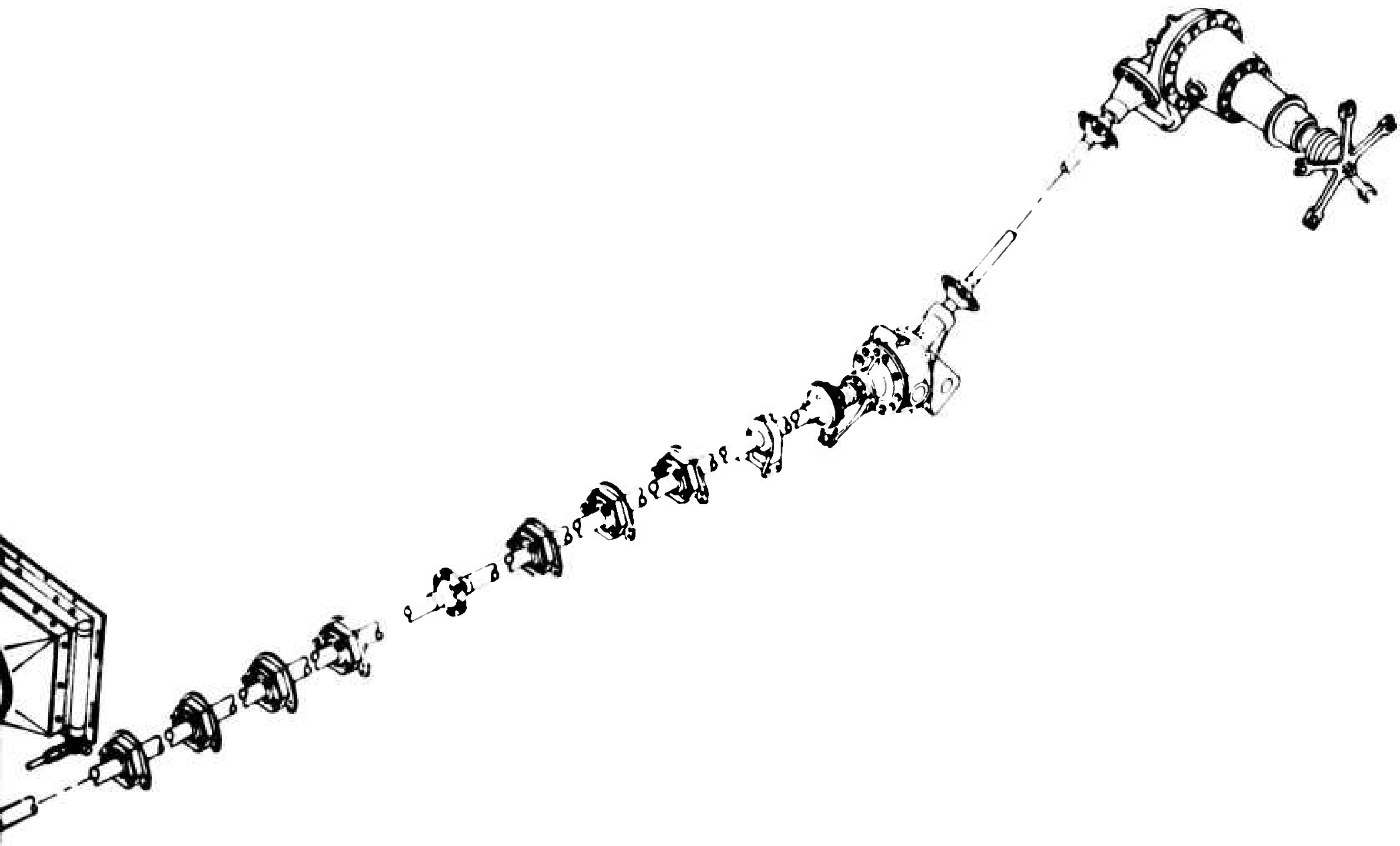
S-61L

HH-3C

SH-3D

Figure 1. H-3 Series Helicopters.

Figure 2. H-3 Rotor and Transmission System.



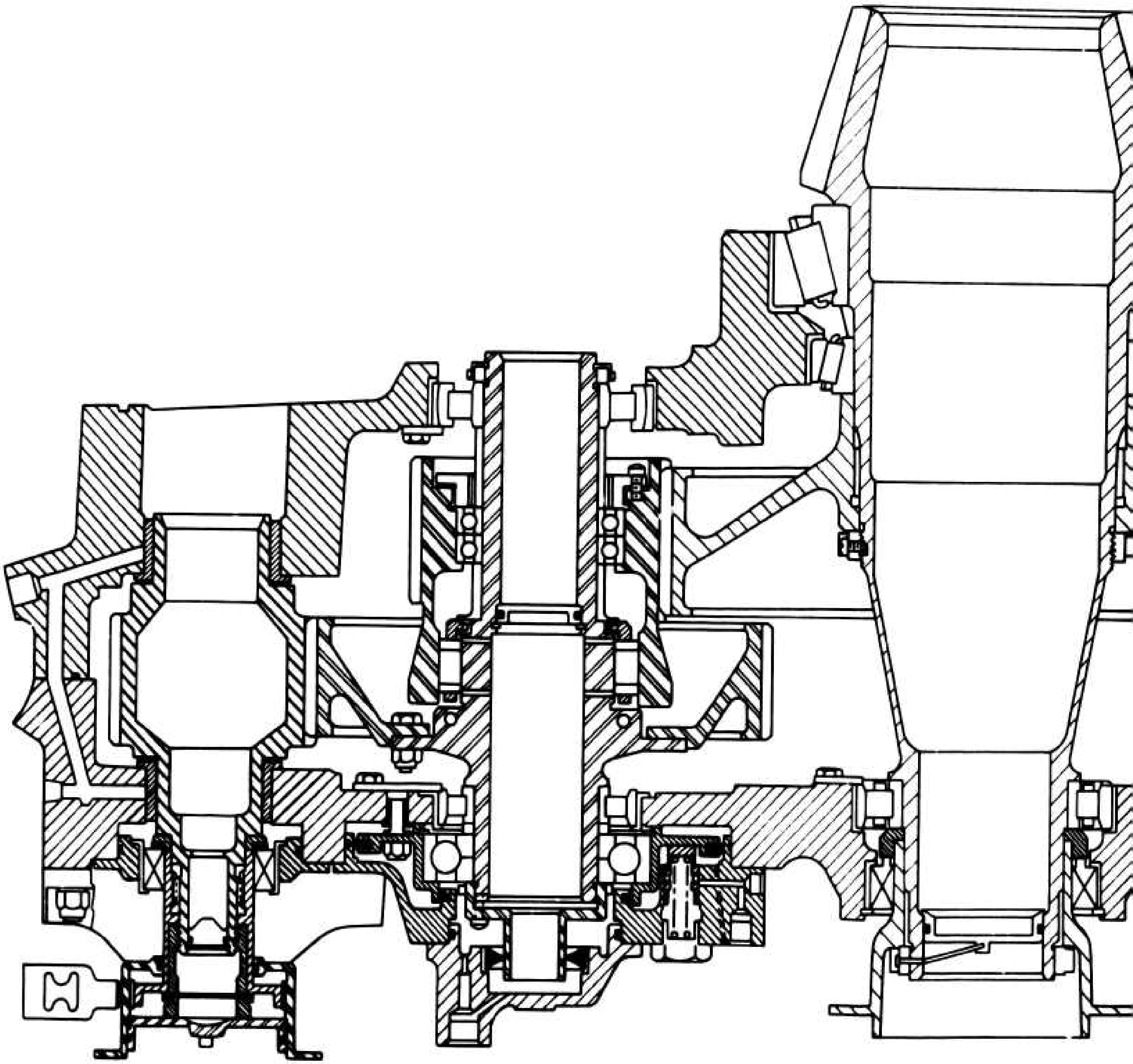
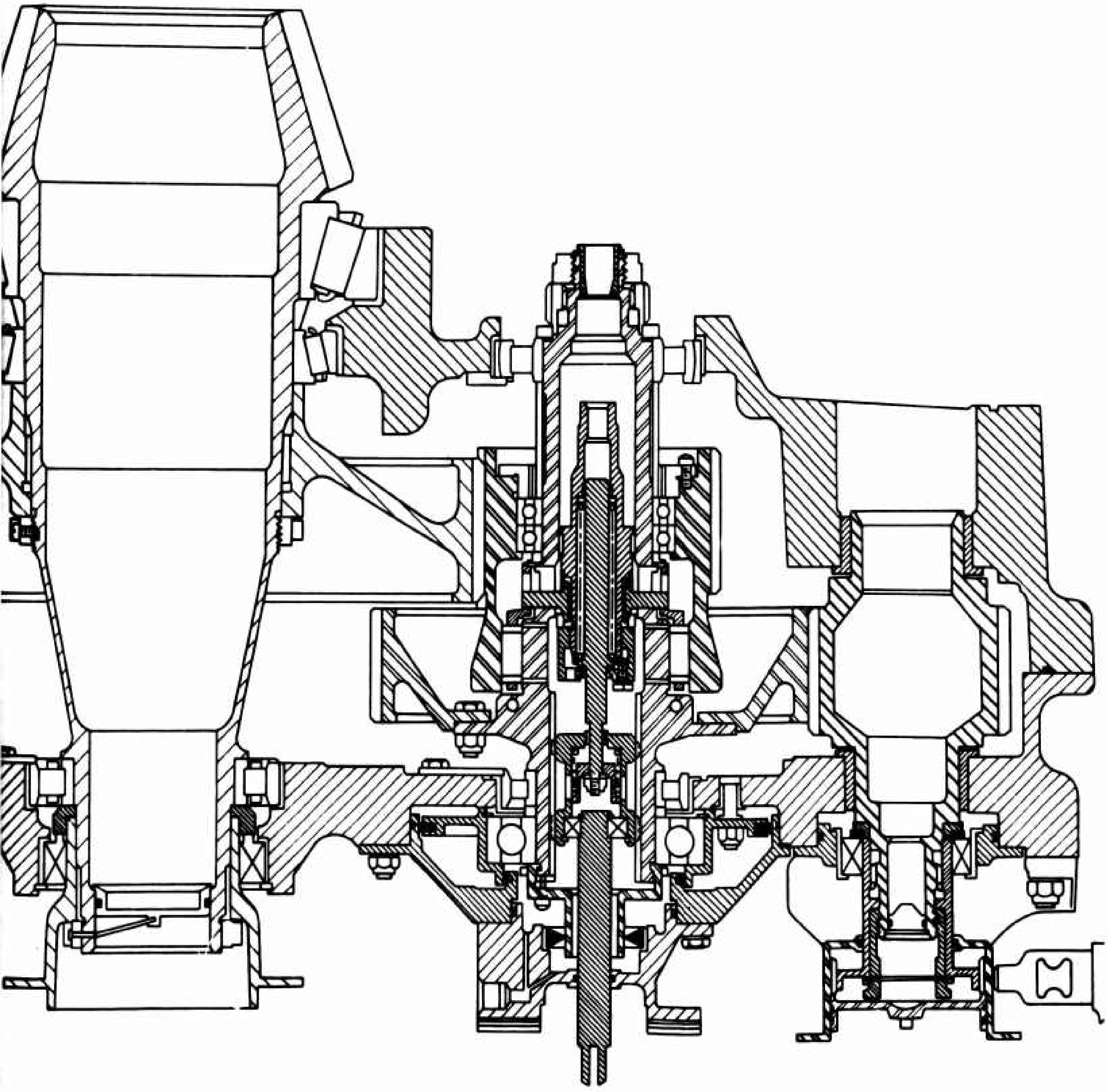


Figure 3. Input Section, Main Gearbox.

Preceding page blank



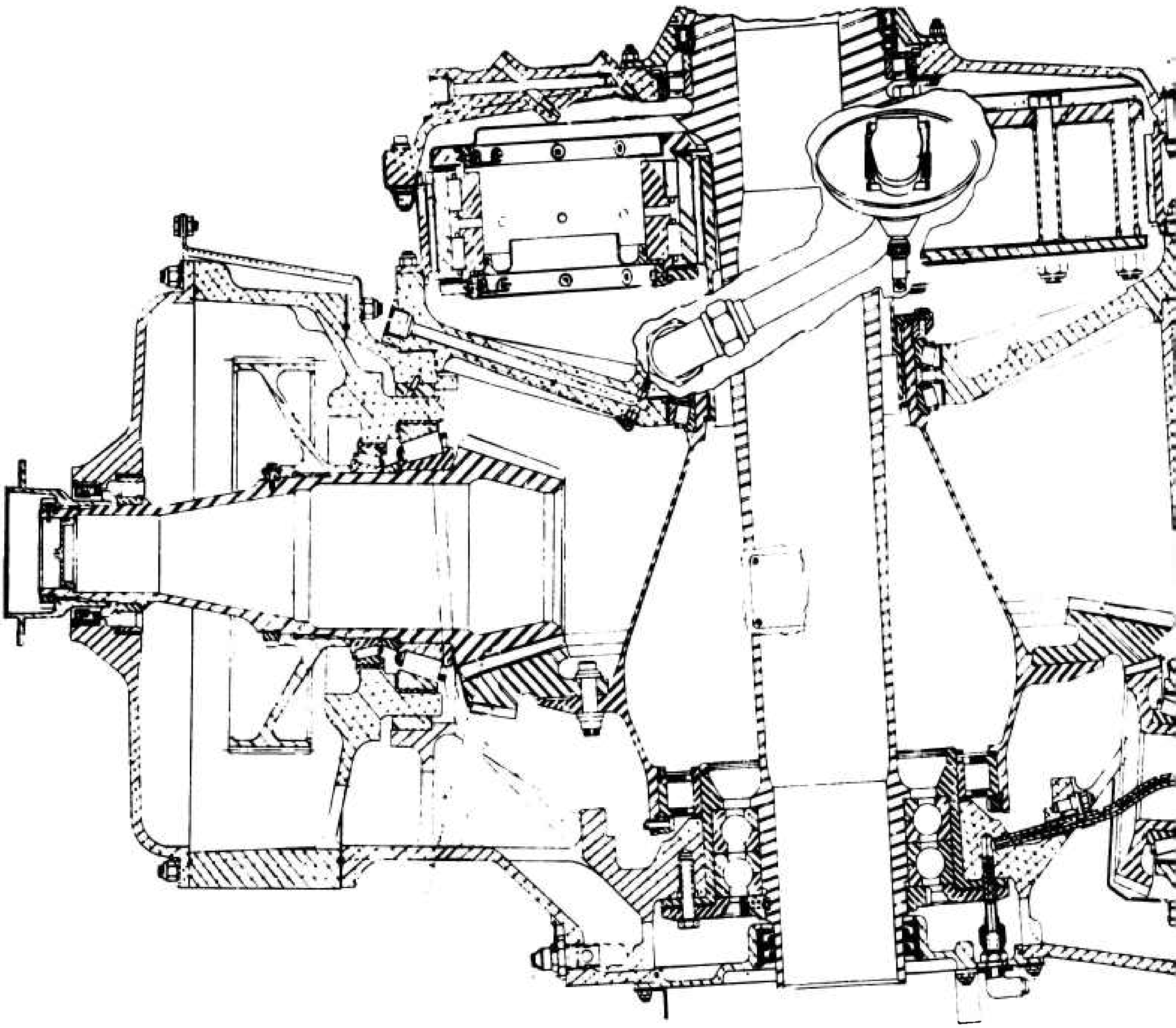
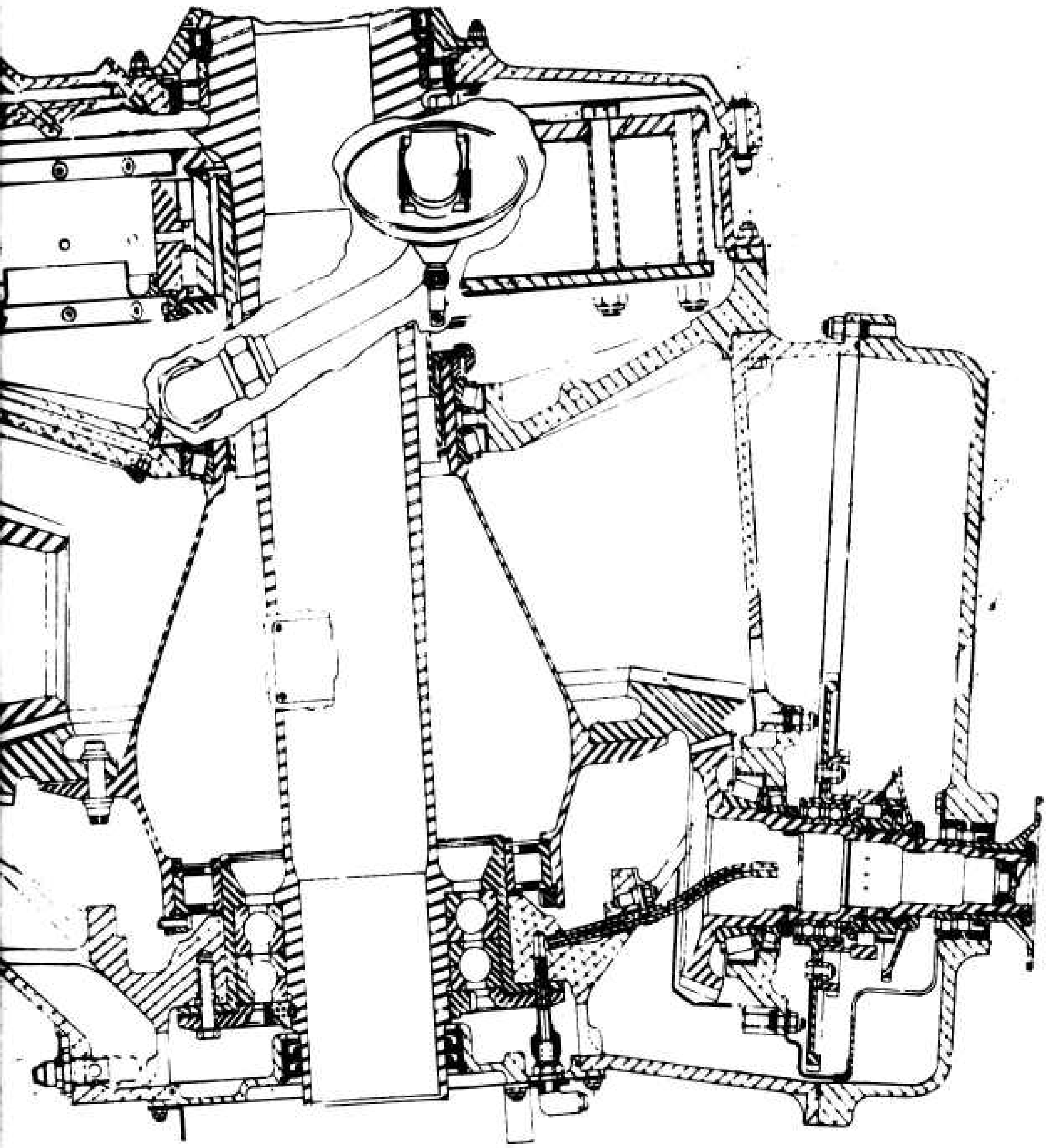


Figure 4. Main Gearbox, Section View.

Preceding page blank



, Section View.

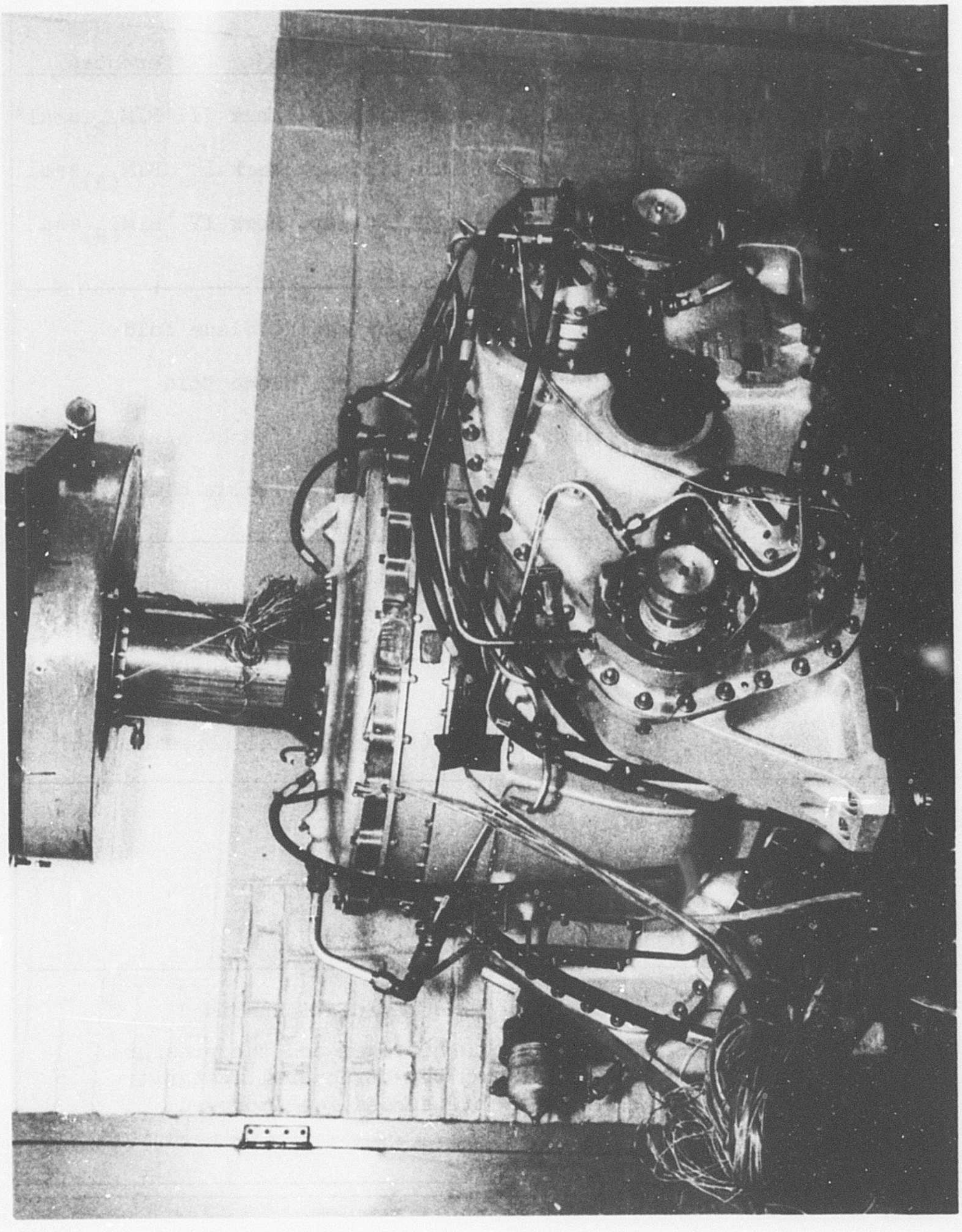


Figure 5. H-3 Main Gearbox.

Preceding page blank

TABLE I. MAJOR DIFFERENCES, H-3/S-61 ROTOR SYSTEMS

	Military or Commercial Designation	Major Differences
Main Rotor Blade	SH-3A/D	18-inch tip cap, Mark III $BIM_{(R)}$ seal*
	S-61L/N	22-inch tip cap, Mark I $BIM_{(R)}$ seal
	CH-3C/E	22-inch tip cap, Mark IV $BIM_{(R)}$ seal
Main Rotor Head	SH-3A	Grease lubricated, blade fold
	SH-3D	Oil lubricated, blade fold
	S-61L/N	Oil lubricated, without blade fold
	CH-3C	Oil lubricated, without blade fold
Tail Rotor Blade	SH-3A/D	Aluminum wear strip, short stainless steel abrasion strip
	S-61L/N	Aluminum wear strip, short stainless steel abrasion strip
	CH-3C	Long stainless steel abrasion strip
Tail Rotor Head	SH-3A/D	Grease lubricated
	S-61L/N	Grease lubricated
	CH-3C	Oil lubricated

*$BIM_{(R)}$ seal is a patented Sikorsky Blade Inspection Method in which the spar is pressurized with nitrogen and the pressure in the spar provides an indication of the structural integrity of the blade. Mark I, III, and IV are successive improved versions of the system.

mesh to reduce the speed to 8,100 rpm. This speed permits a ramp-roller type freewheel unit to be installed, providing isolation of the turbines should a malfunction occur. The left-hand freewheel unit includes an actuator which prevents the freewheel unit from being engaged but allows the inner shaft to rotate and drive the accessories during ground operation when the main rotor is stationary. Helical gears are used to reduce the speed to 3,195 rpm and to combine the power from both engines onto a single shaft. The thrust from these helical pinions is impressed on two hydraulic cylinders and provides the input for the two torquemeters used in this aircraft. The combined power is transferred across an approximately right-angle shaft angle by the use of spiral bevel gears and to the one-stage planetary that supplies power to the main rotor. Power from the driven bevel gear is also supplied to the tail rotor drive system and the accessories as well.

The tail rotor drive system, shown in Figure 2, includes a drive shaft rotating at 3,030 rpm, an intermediate gearbox (shown in Figure 6), and a tail gearbox (shown in Figure 7). The intermediate gearbox is only an angular change unit, while the tail gearbox accomplishes a 2.4375 speed reduction with a right-angle set of spiral bevel gears. The output spiral bevel gear shaft is the mounting shaft for the tail rotor, while the pitch beam shaft is mounted concentric with and is located within this same output shaft.

Description of Main Rotor System

This H-3 aircraft was initially developed for carrier operation with the U.S. Navy and featured automatic blade folding as shown in Figure 8. The fully articulated main rotor is shown in Figures 9 and 10. Some subsequent commercial and military versions of this rotor system have this feature removed, and a much more simple rotor head assembly has resulted at a substantial reduction in weight. Oil- and grease-lubricated versions of both configurations were produced as noted in Table I. An oil-lubricated rotor head without blade fold is shown in Figure 10.

As can be seen in Figure 11, the integral upper plate and hub are splined to the rotor shaft to transmit the torque to the rotor head. The lower plate, capable of transmitting only centrifugal force, is attached to the hub and encloses the vertical and horizontal hinge, the damper assemblies, and other miscellaneous hardware. The rotor head is mounted on and secured to the main rotor shaft by two tapered cone seats and a large-diameter nut.

A vertical and horizontal hinge is fitted into each arm of the hub assembly between the hub plates. These hinges allow lead-lag and flapping motions about intersecting axes. The oil-lubricated rotor heads have oil tanks which are located on top of the vertical hinge to provide for oil lubrication of the vertical and horizontal hinges and sleeve and spindle assemblies; a hydraulic damper is attached to one end of each horizontal pin and to an adjacent arm on the hub, as shown in Figure 10, providing for attenuation of rotor blade lead-lag motion about the vertical hinge. The cylinder is connected to a central reservoir for continuous replenishment

of hydraulic fluid. A sleeve and spindle assembly is connected to the horizontal hinge and includes a stack of angular contact ball bearings which form the feathering hinge. These bearings allow rotation of the sleeve and blade for pitch change motion. Each main rotor blade is joined to the sleeve by a bolted connection.

The rotor blades are controlled by a swashplate system that is concentric with the main rotor shaft. The nonrotating swashplate is mounted on a sliding journal type bearing and a large spherical joint that permit translation and angular tilt, respectively, as required by the servo inputs of the control system. A nonrotating scissors linkage provides for synchronization of the nonrotating swashplate with the main rotor transmission housing, while allowing the axial and angular freedom required. The main rotor servos are attached directly to this swashplate and provide the basic collective and cyclic pitch input signal to the main rotor head. A large-diameter duplex set of ball bearings joins the nonrotating to the rotating swashplate, as shown in Figure 12.

A control horn is bolted to each sleeve, and the motions of the swashplate are transferred to the horns by five control rods. A rotating scissors provides for synchronization of the rotating swashplate with the main rotor while allowing the swashplate to simultaneously translate and tilt on its axis.

Details of the main rotor blade are shown in Figure 13. The blade is essentially all metal and has a structure consisting of two primary members, a spar which spans nearly the full length of the blade, and a cuff which retains the spar and transfer loads to the rotor head. Secondary structural members retain leading-edge counterweights and shim weights used for spanwise and chordwise balance. All other parts are nonstructural and are included for balancing, sealing, and aerodynamic purposes. They consist of trailing-edge fairings, root end spacer blocks, a tip cap, leading-edge counterweights, and spar and fairing seals.

The aluminum alloy spar in the shape of a hollow "D" forms the leading edge of the airfoil section and is the primary structural member. It has a constant inner contour over the entire spar length. The wall thickness increases gradually, going inboard and ending in an appropriately thick root end section of sufficient strength to carry all centrifugal, torsional, and bending stresses.

The aft portion of the airfoil contour is formed by sheet metal fairings which are bonded to the aft portion of the spar. Closely spaced reinforcing ribs stiffen the fairings and prevent local panel flutter. The 12-inch-long fairings are nonstructural units, consisting of aluminum alloy formed ribs and outer skins adhesively bonded together. Spaces between fairings are sealed with wedges of closed-cell, nitrogen-filled neoprene sponge. The inboard end of the blade has no fairings, as shown in Figure 9.

Nonstructural counterweights, each covered with a molded-on jacket of rubber to produce an interference fit without metal-to-metal contact, are

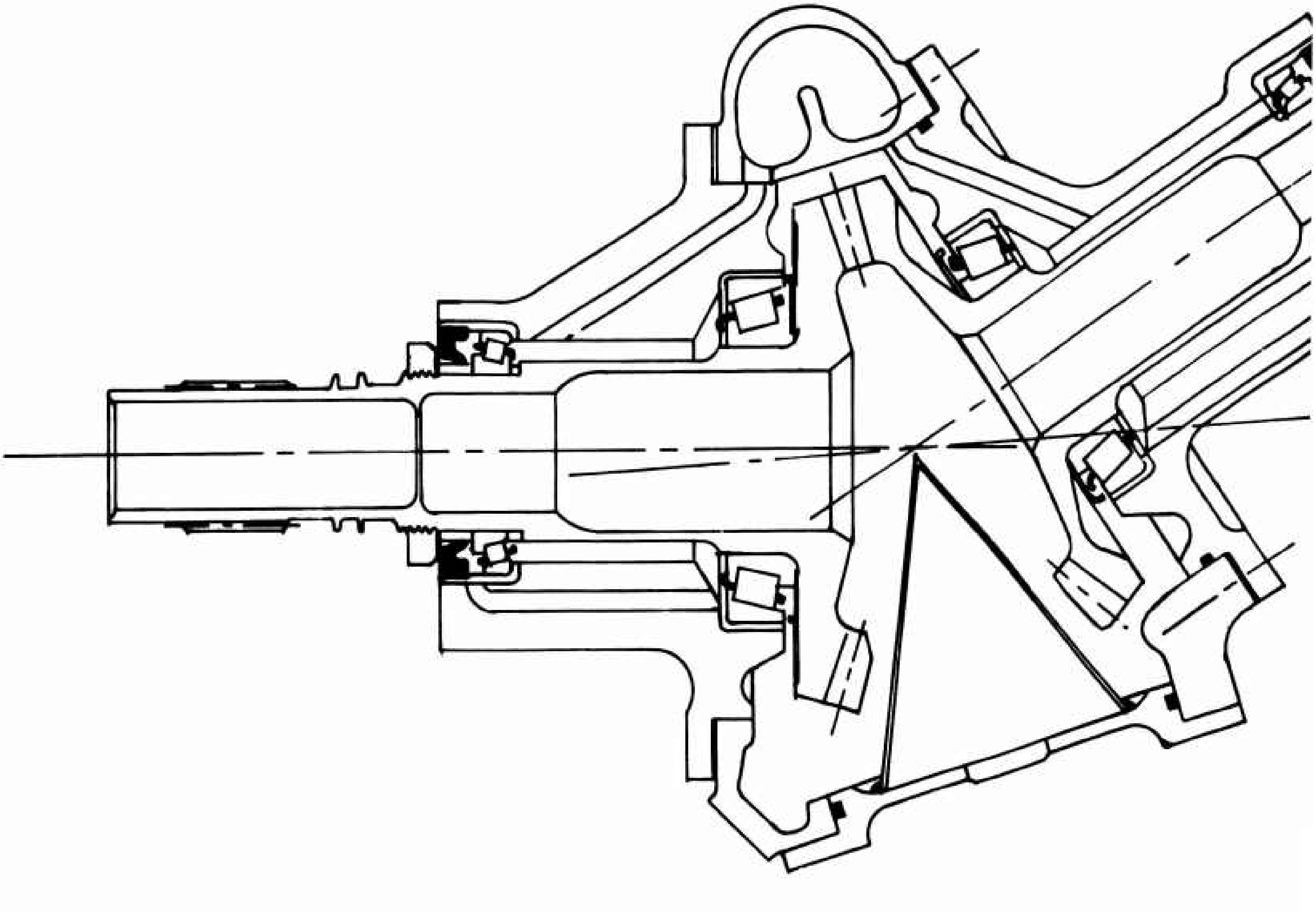
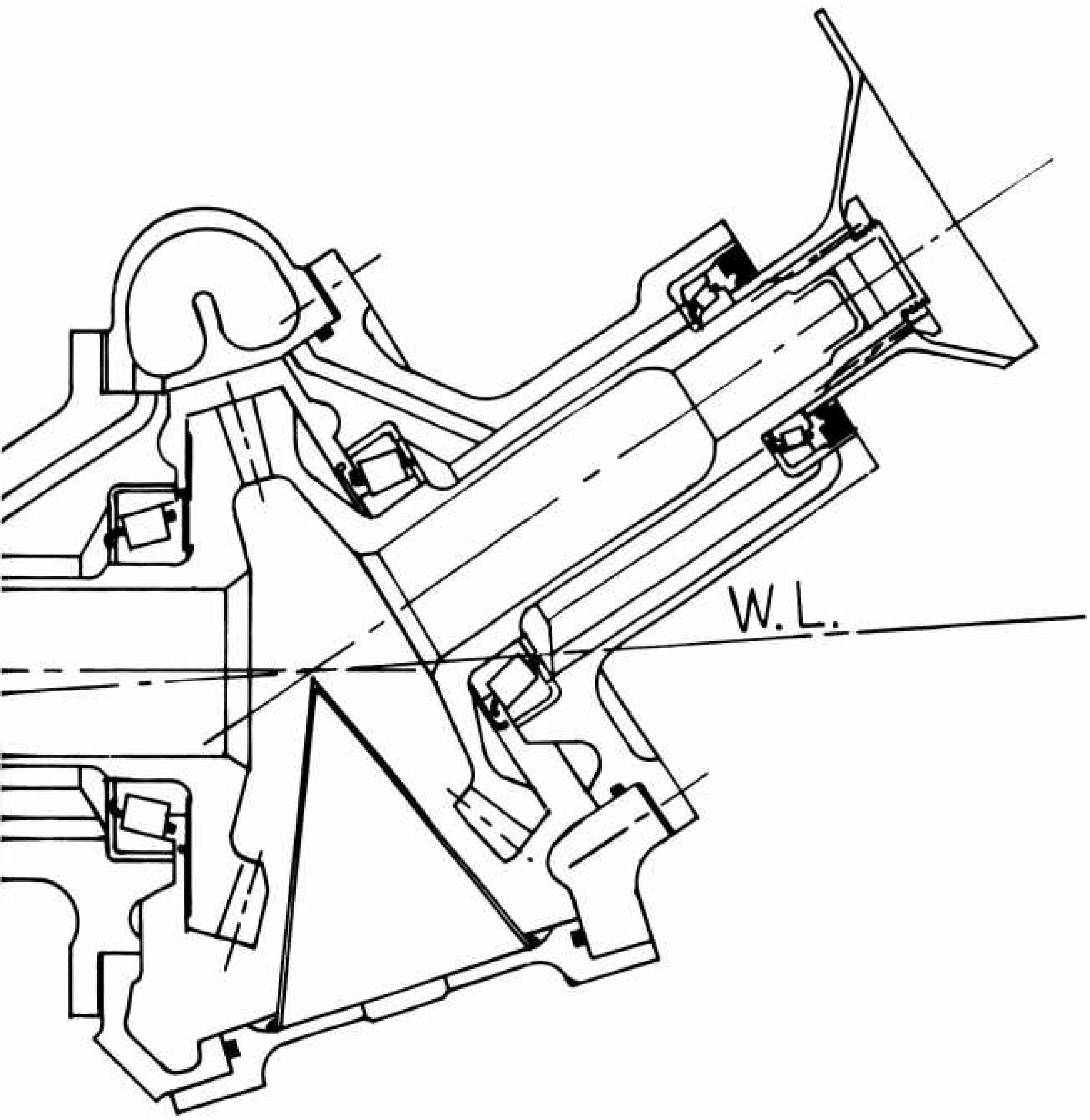


Figure 6. Intermediate Gearbox.



box.

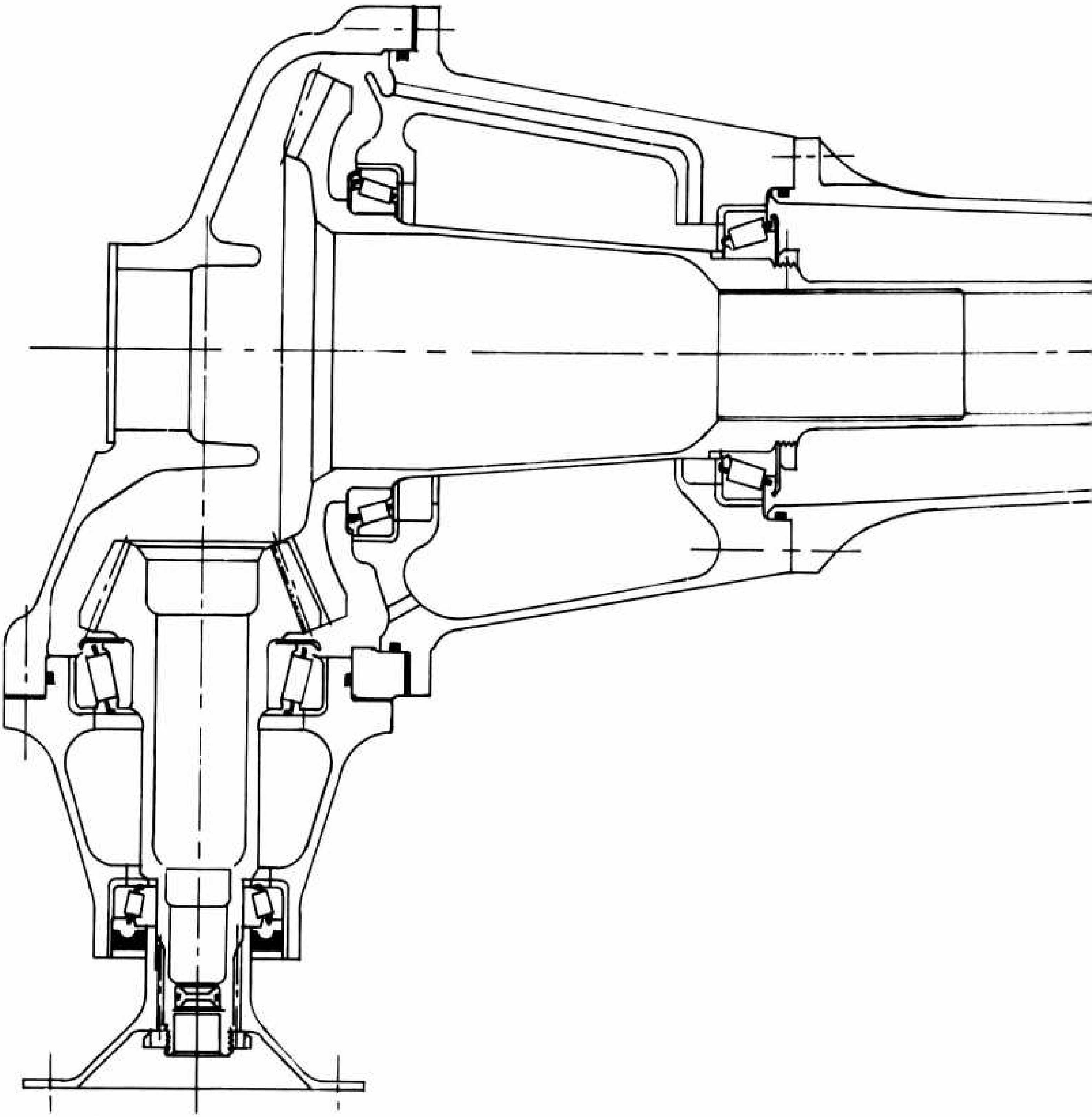
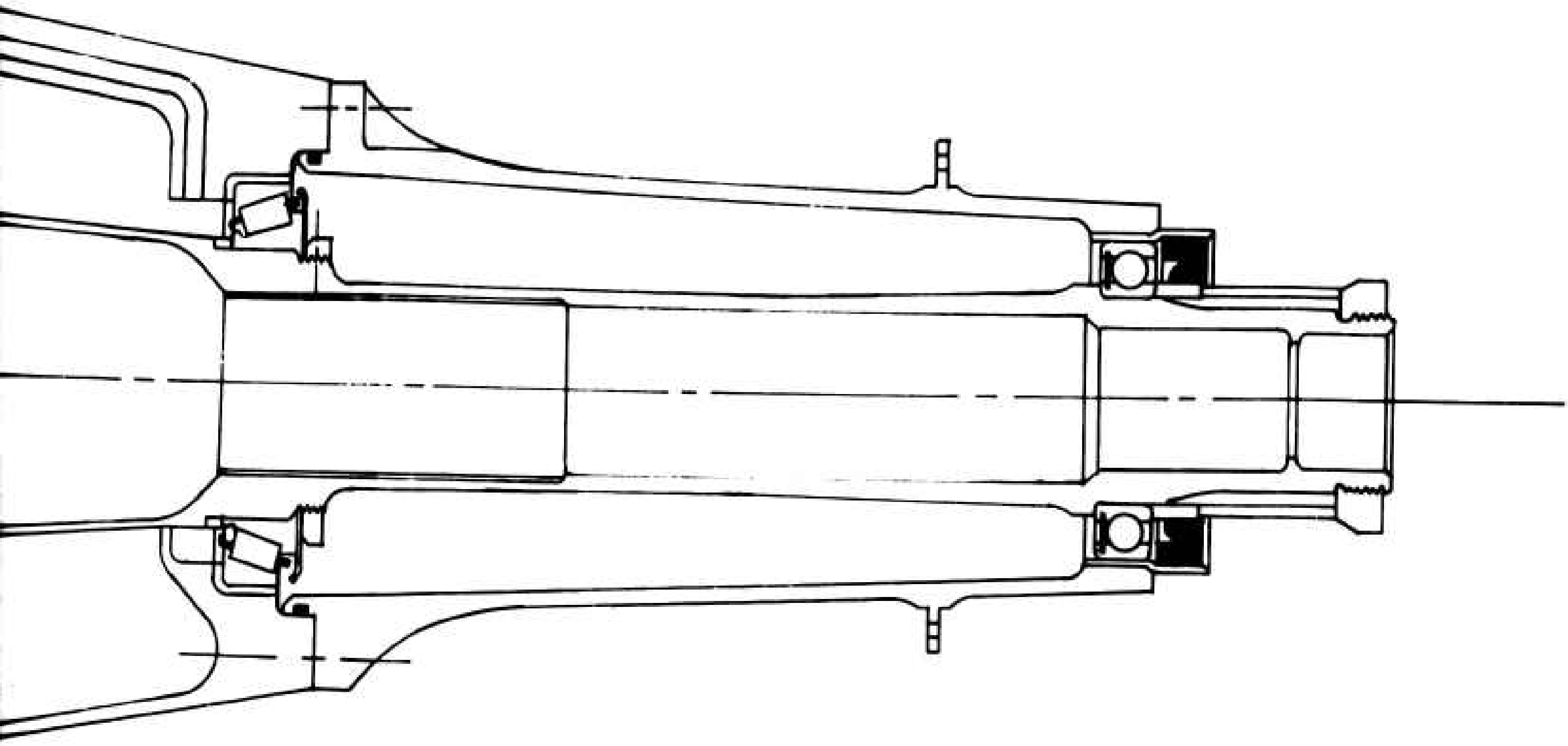


Figure 7. Tail Gearbox.

Preceding page blank



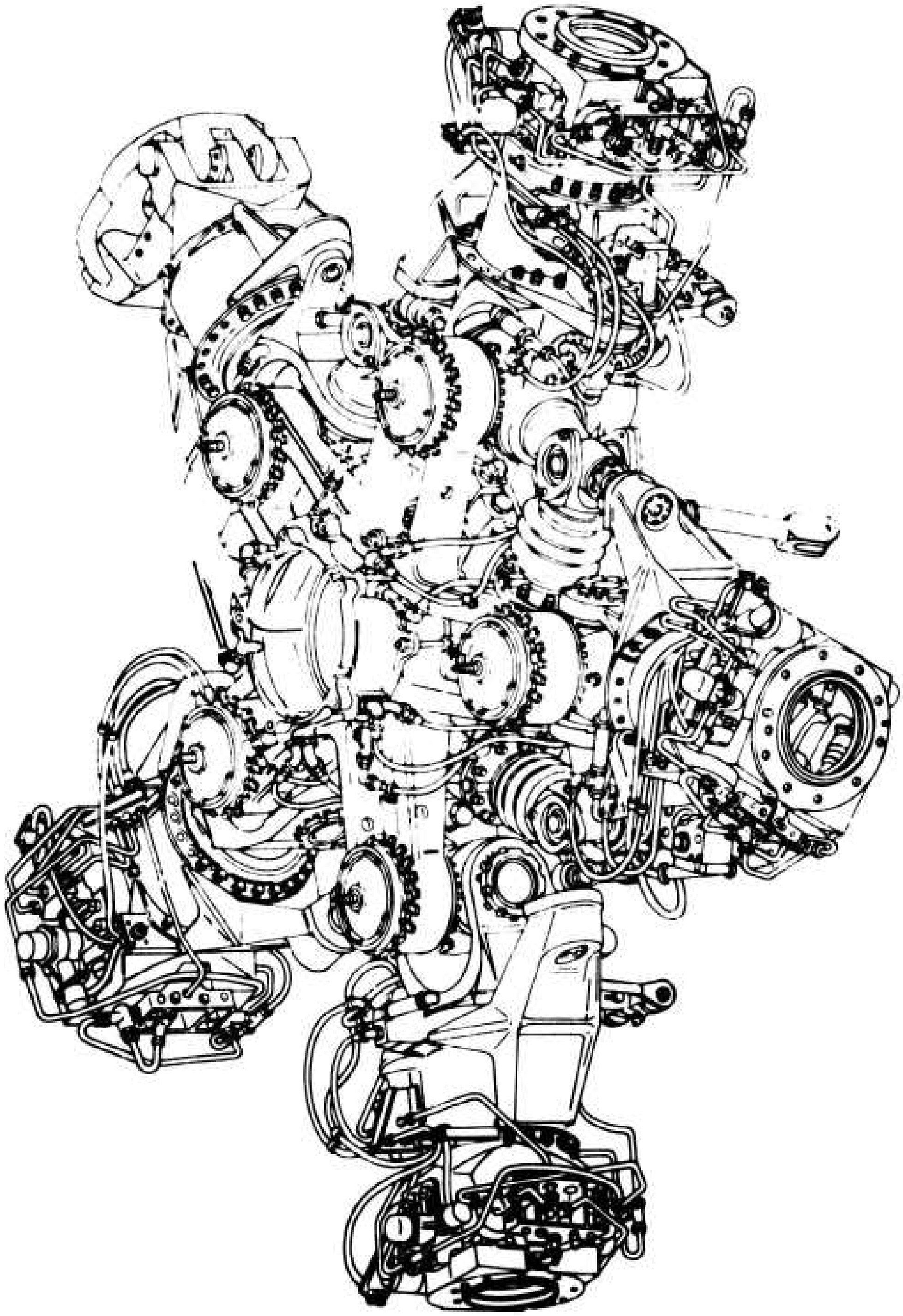


Figure 8. Main Rotor Head With Blade Fold.

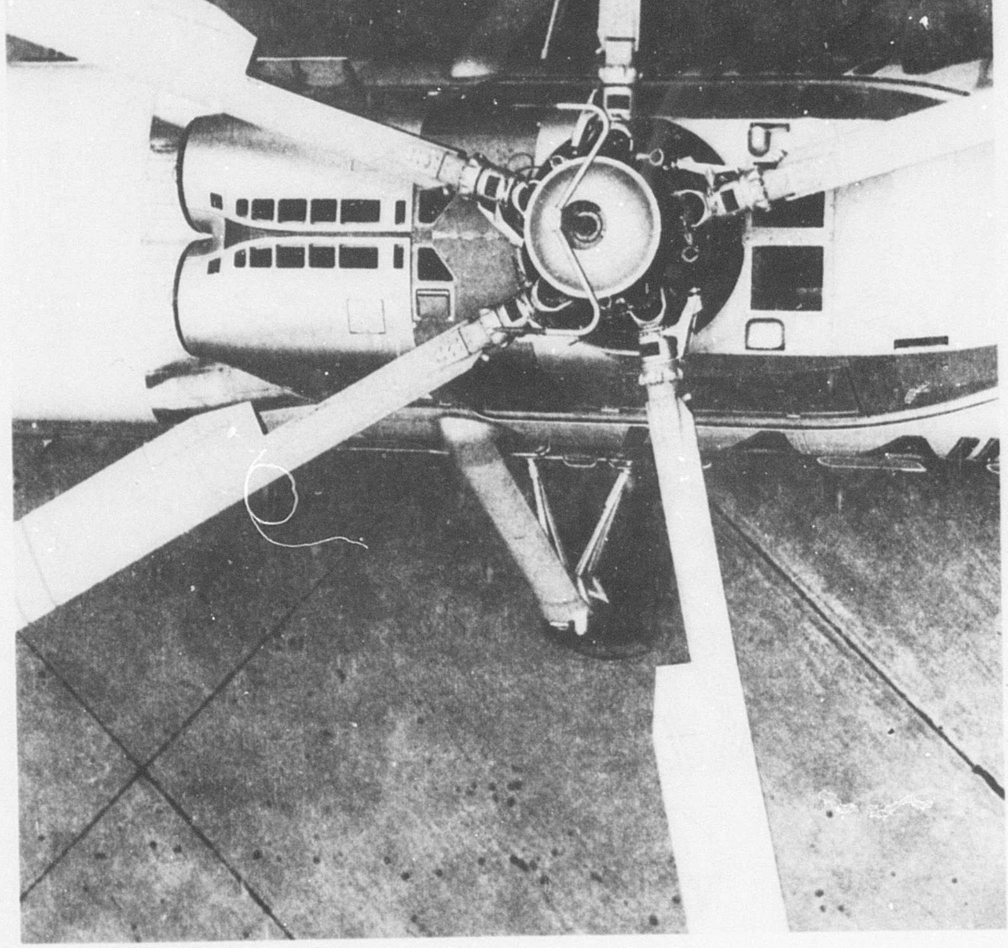


Figure 9. Plan View, H-3 Oil Lubricated Main Rotor Head.

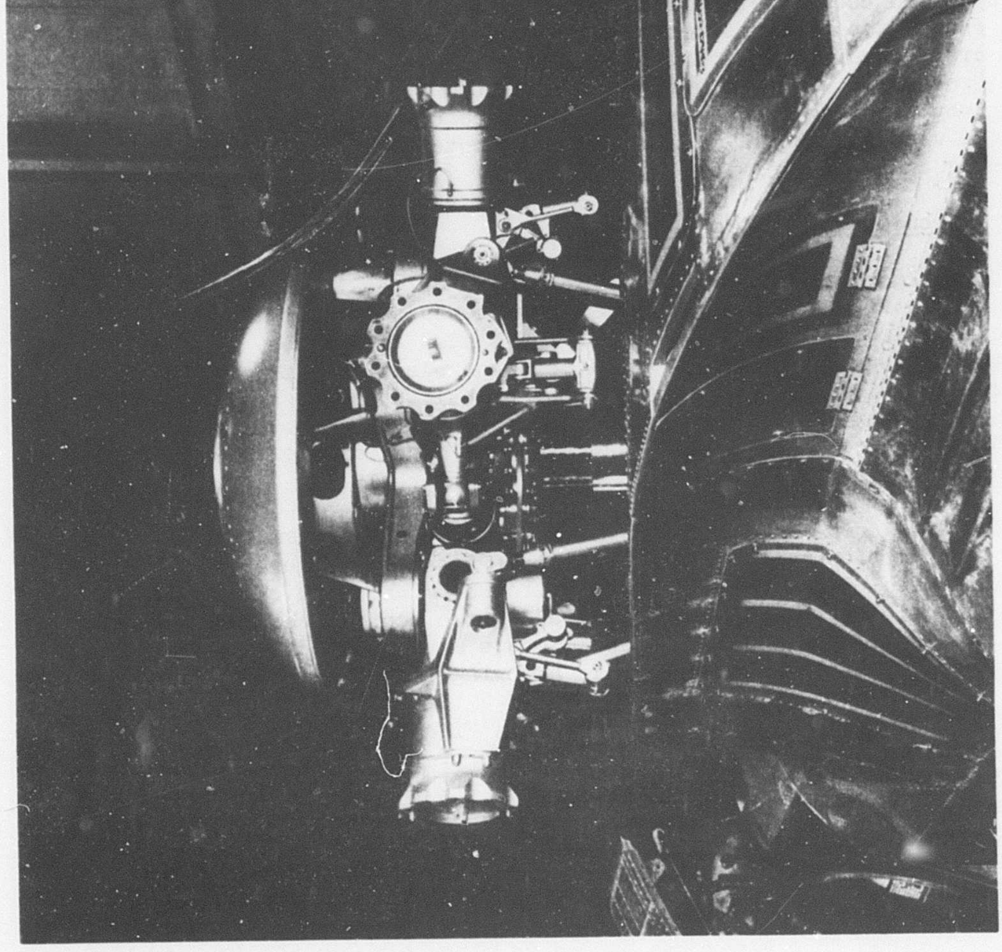


Figure 10. Side View, H-3 Oil Lubricated Main Rotor Head.

installed in the leading edge of the spar. At the tip, shim weights are used to match the spanwise balance of each blade against a master, in a static balancing operation. Another weight is selectively positioned along a tip bracket to match the chordwise balance of the blade against a master in a dynamic balancing operation on the whirl stand.

The tip cap is a rectangular, nonstructural type fairing formed from aluminum alloy. Each cap, like the blade, is statically balanced to a standard moment to provide interchangeability. The cap is retained by screws fastened to nut plates attached to the spar, the extending horn, and tip pocket rib, and is readily removable to provide easy access to tip hardware.

The blade is equipped with the Sikorsky-developed blade inspection method ($BIM_{(R)}$). The spar is sealed and pressurized from its root end to just inboard of the counterweight retaining block. An indicator mounted at the root end of the blade senses pressure losses caused by cracks in the spar. If a crack occurs, the indicator will display a red warning color and is easily observed from the ground. The system provides a fail-safe blade design by exposing cracks safely in advance of complete propagation. This system, used in H-34, H-3, and H-53 helicopters, has been flawless in uncovering cracks in service.

Description of Antitorque Rotor System

The five-bladed tail rotor system installed on the initial H-3 helicopters is shown in Figure 14. The primary components are the tail rotor hub, spindles, sleeve, control arms, and the blades themselves. The tail rotor has two degrees of freedom. The sleeve and blade assembly rotates about the spindle on a stack of angular contact ball bearings that form the feathering hinge for pitch change motion, while the sleeve, blade, and spindle are free to move about the flapping hinge axis of the tail rotor hub. The bearing arrangement is shown in Figure 15.

A pitch arm, or horn, is bolted to each sleeve and transmits the input pitch link motion to the sleeve and blade assembly (Figure 15). The adjustable pitch link connects to the pitch beam where it receives the input control motions from the pitch beam and pitch control shaft. The pitch beam, actuator shaft, and hub assembly are synchronized to provide the required geometric relationship while allowing the pitch beam to move axially.

The tail rotor blade assembly is shown in Figure 16. The primary structural supporting member extends the length of the blade and consists of a solid aluminum alloy spar. This spar has a thin leading-edge section for the outer 75 percent of the blade but develops into a substantially thicker section at the inboard root end where it attaches to the sleeve. A continuous aluminum alloy skin is wrapped around and bonded to the leading edge of the spar and also bonded together at the trailing edge, forming an integral assembly. The interior of the skin is provided with sandwiched aluminum foil honeycomb bonded in place between the top and bottom skin and the trailing-edge side of the spar to form structural support for the skin and to produce a lightweight blade. Chordwise and spanwise balance weights are fastened to the inside tip of the skin and the spar prior

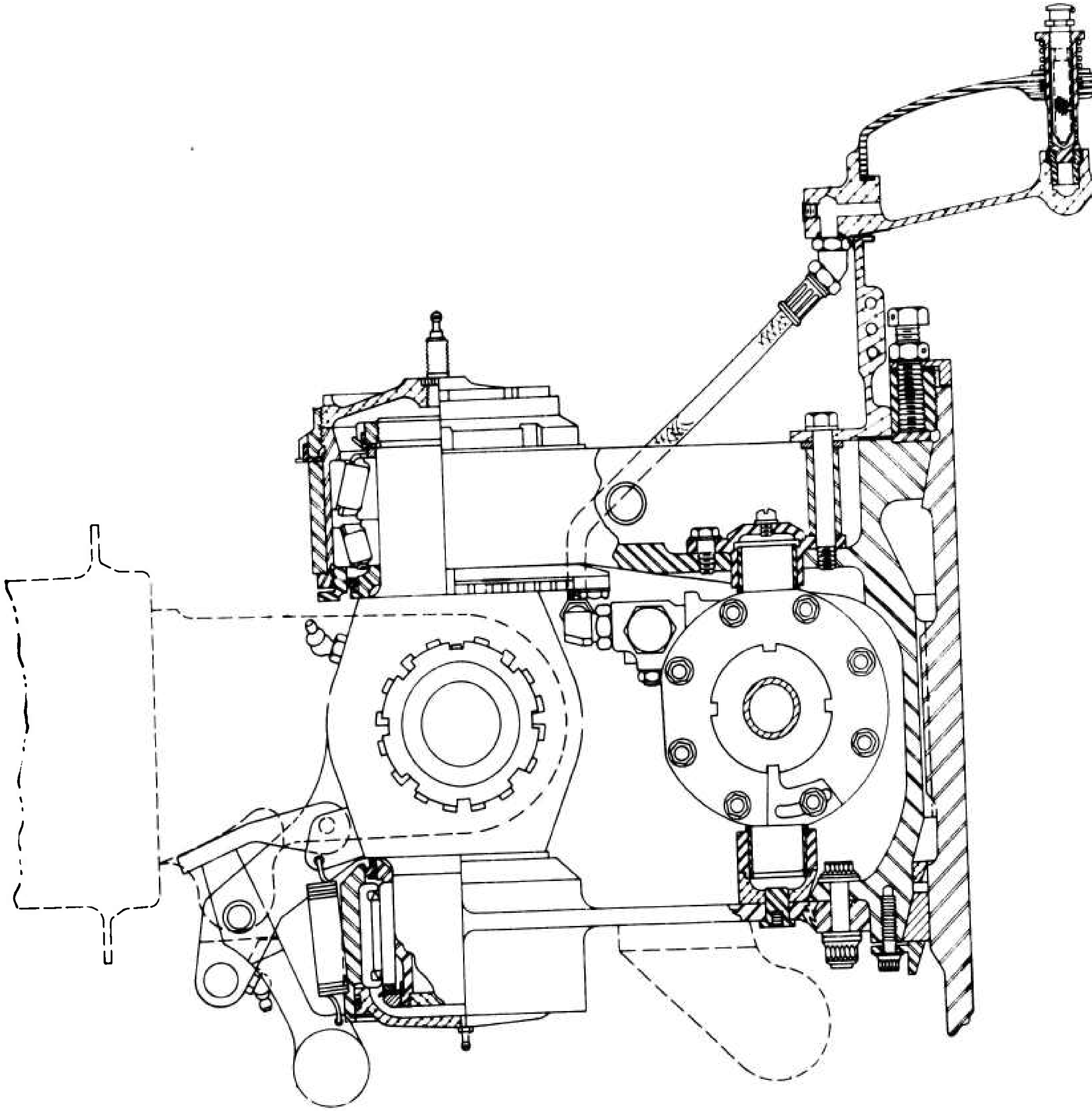
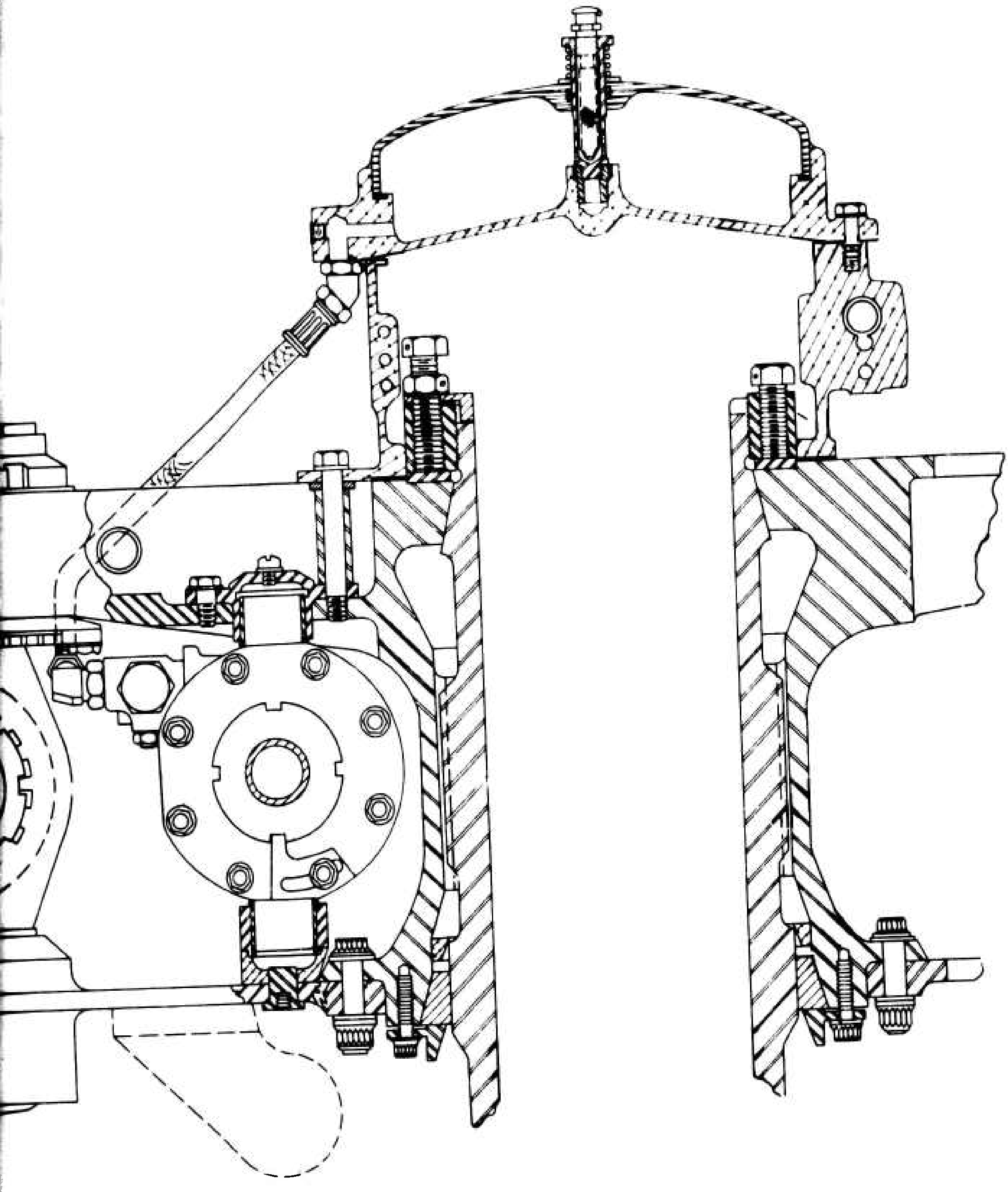


Figure 11. Main Rotor Head, Section View.



tion View.

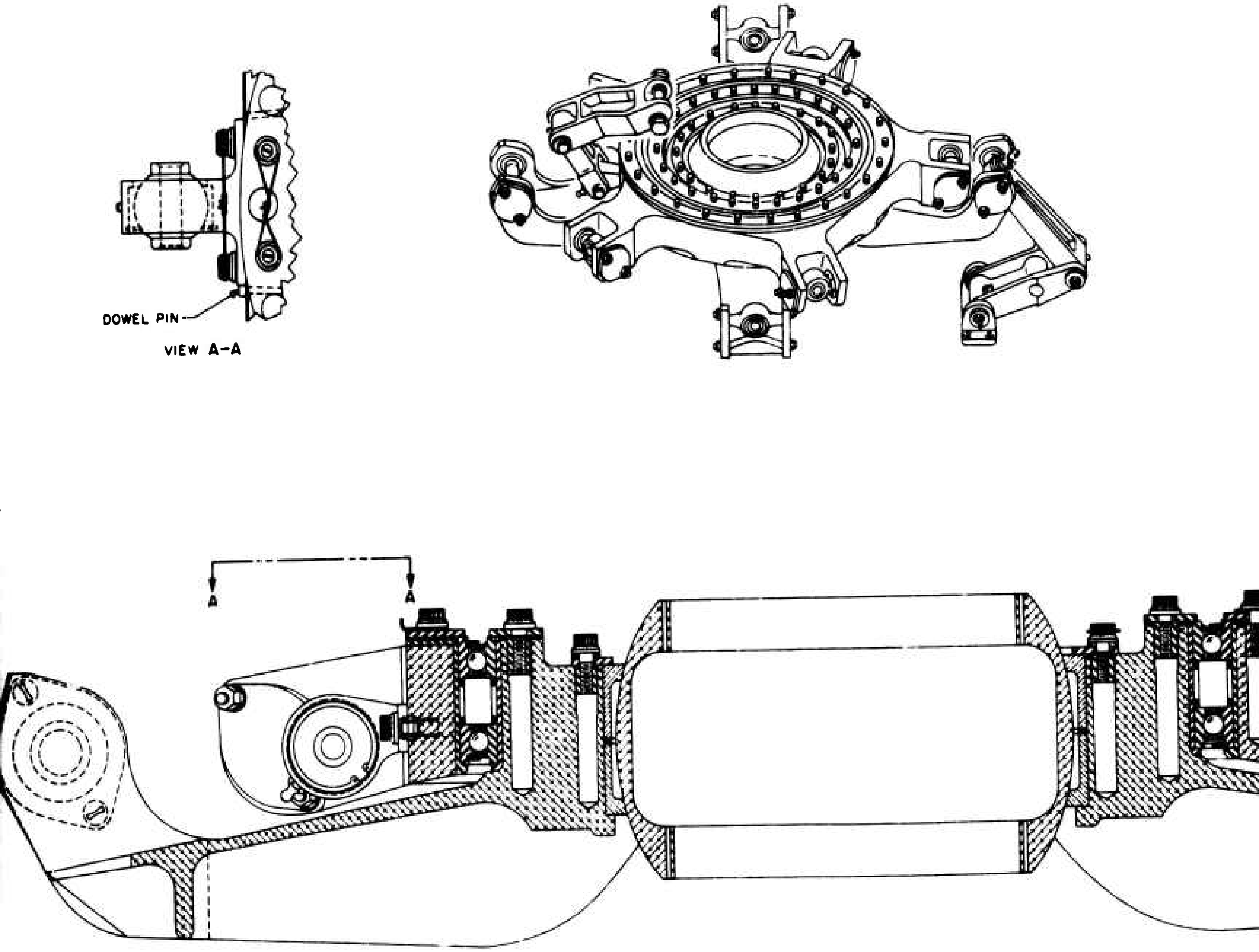
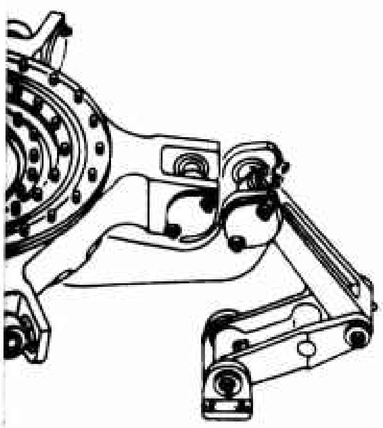
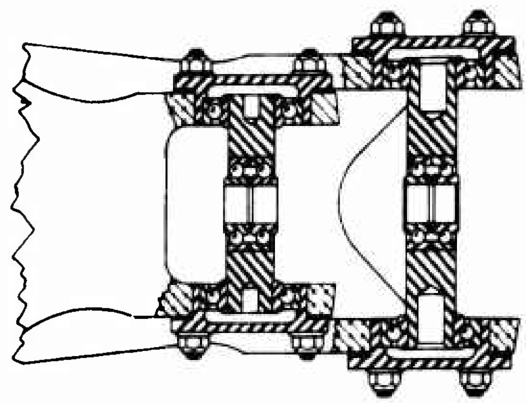
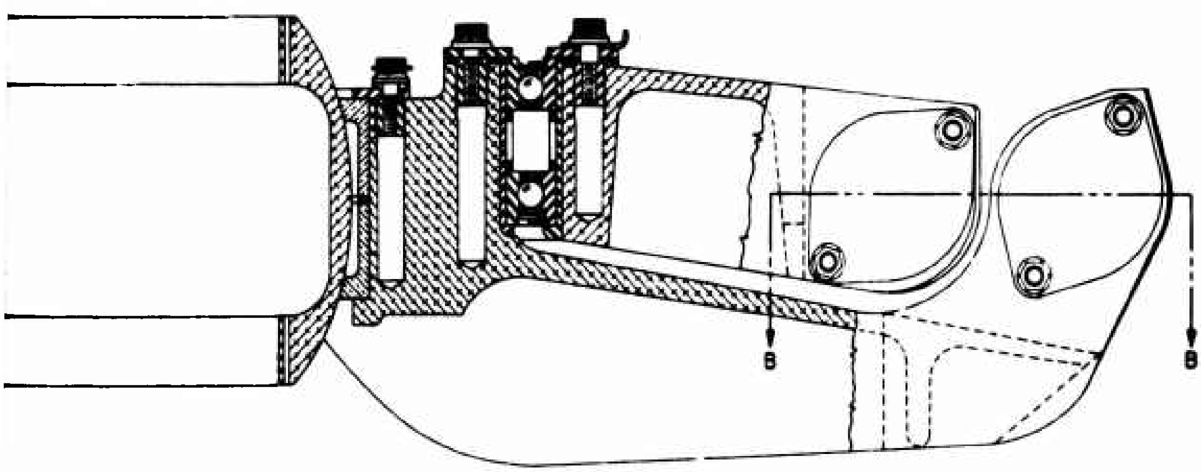


Figure 12. Swashplate Assembly.





VIEW B-B



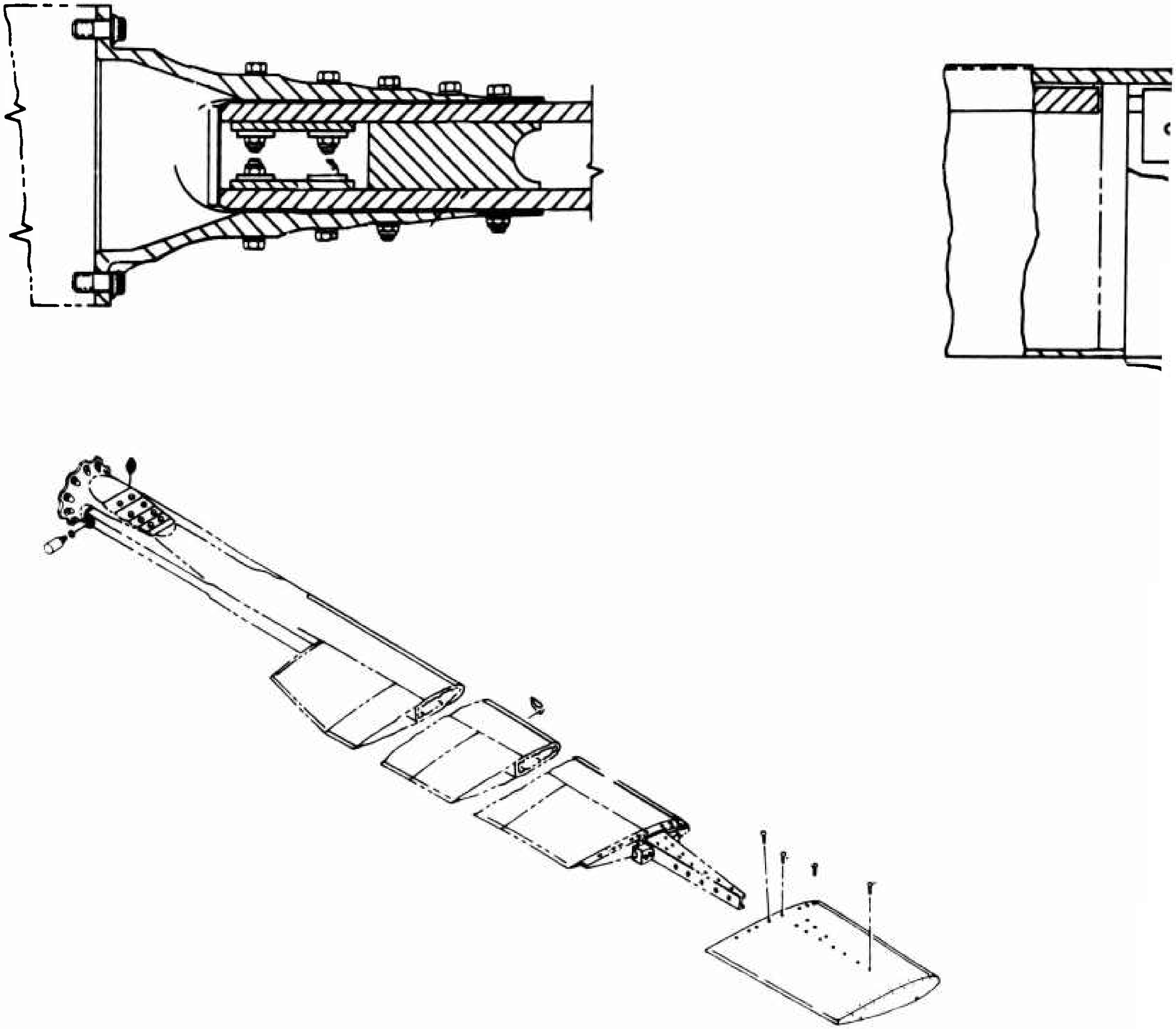
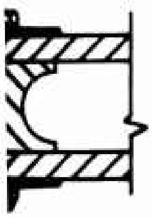
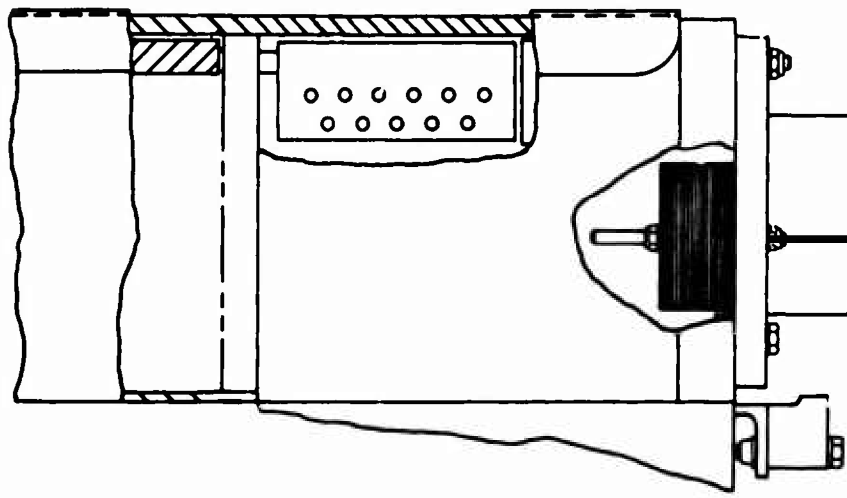
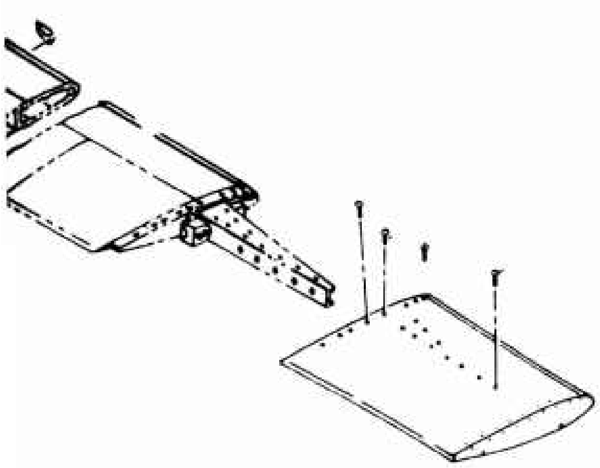
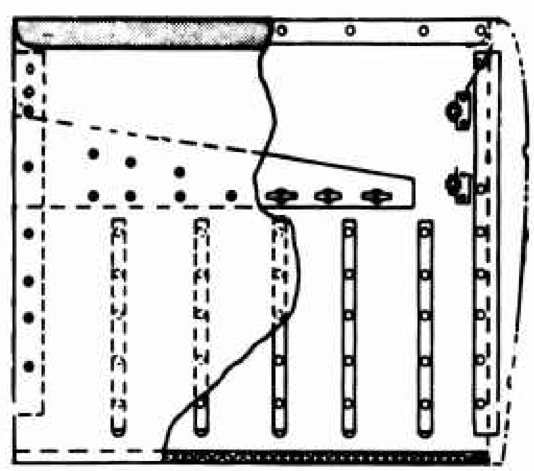


Figure 13. Details of Main Rotor Blade Assembly.









Blade Assembly.

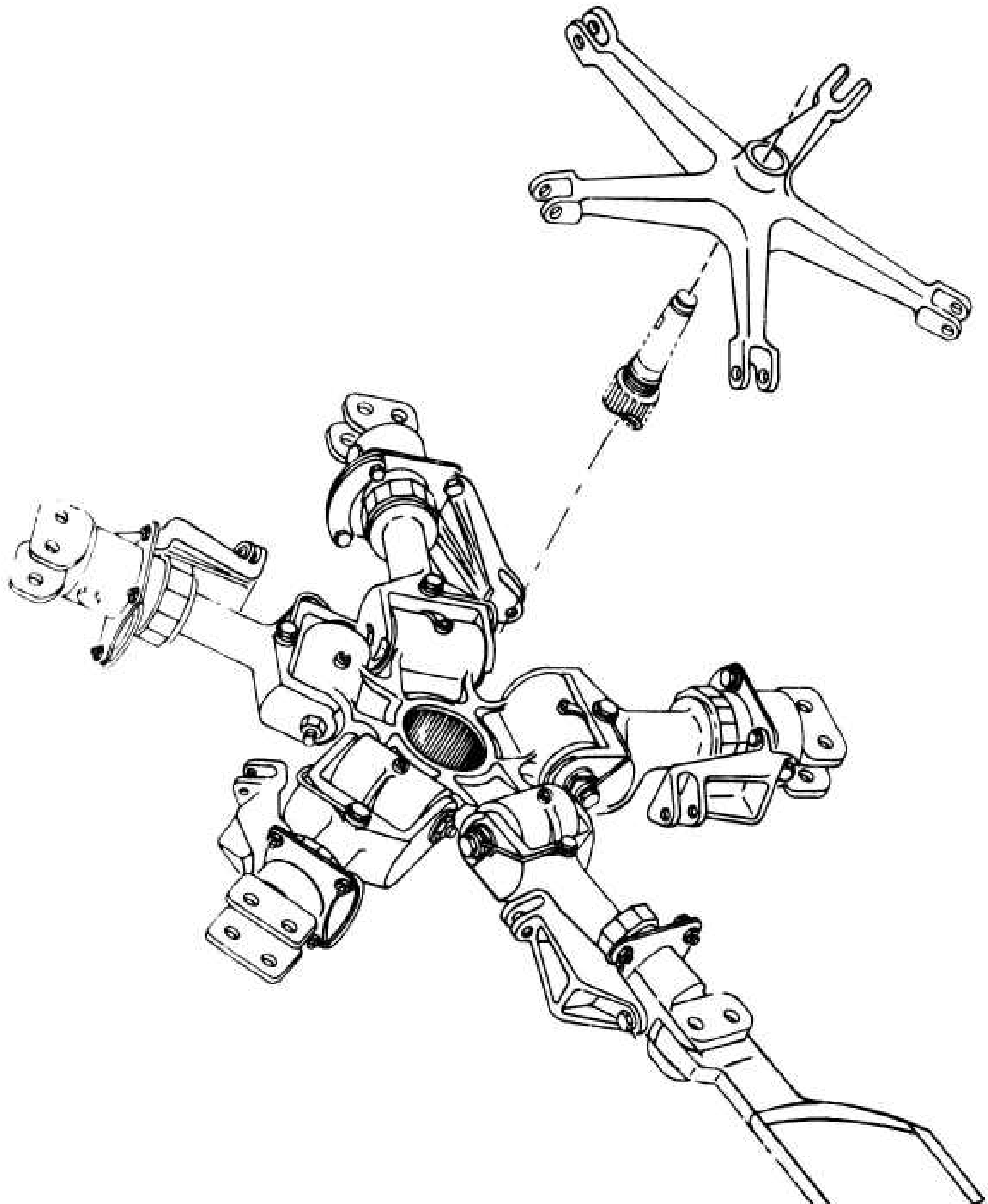


Figure 14. Details of Tail Rotor Assembly.

Preceding page blank

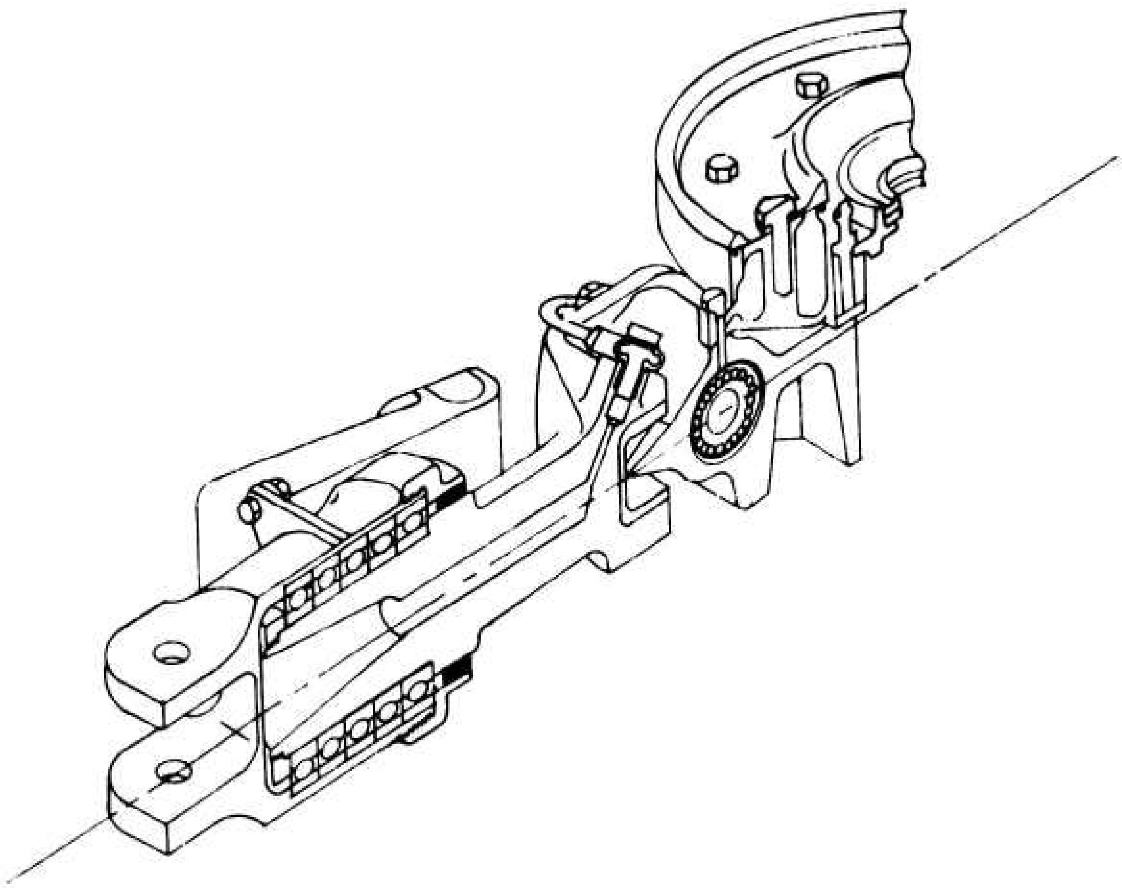


Figure 15. Tail Rotor Bearing Arrangement.

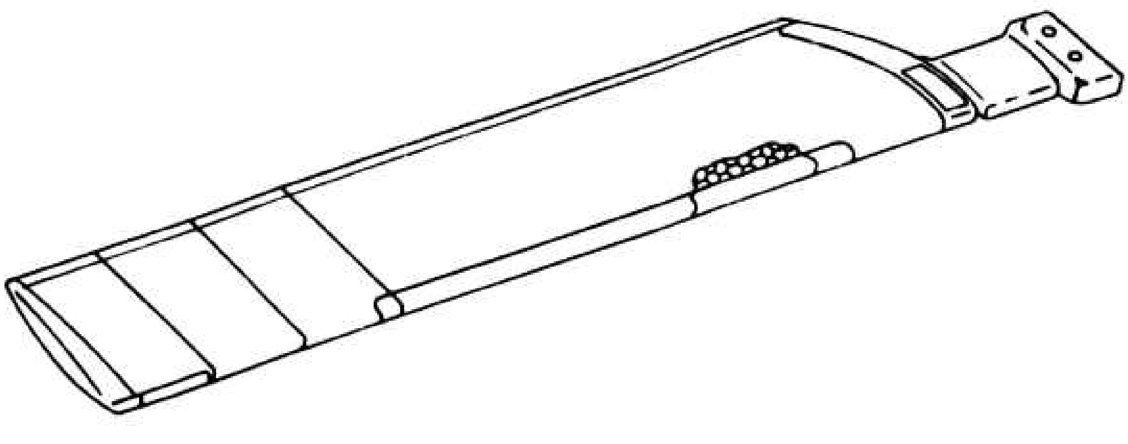


Figure 16. Tail Rotor Blade Assembly.

to installation of the aluminum tip cap. The blades are statically balanced by these weights to a master blade which permits interchangeability of one or more blades on a rotor head. The leading edge of the blade is provided with a bonded-on aluminum wear or stainless steel abrasion strip for the outer portion of the blade. The root end of the blade assembly is sealed with a cemented balsa filler, while the blade is retained to the rotor head sleeve by two bolts.

DESCRIPTION OF TRANSMISSION SYSTEM TEST PROGRAM

The design and development of the H-3 helicopter has been a continuing program for more than 13 years, due to the various applications and missions outlined for this aircraft. To study and evaluate the several facets of the helicopter test program, all aspects of the aircraft program should be considered, including the original design requirements and configuration, the overall test program, and the ensuing model variations that required modification to the dynamic systems and, correspondingly, additional testing. Figure 17 outlines the H-3 helicopter program. Appendix III summarizes the failures experienced on the H-3 development program.

In several aspects, this H-3 program was a pioneer test program for Sikorsky Aircraft. Prior aircraft programs at Sikorsky had used regenerative bench tests, whirl tests, tiedown aircraft tests, and flight tests to develop and qualify the various aircraft components. However, the test program for the dynamic systems of this aircraft commenced on a propulsion test bed using the power from two T58-GE-6 turboshaft engines with a combined output of 2,100 horsepower. This propulsion system test bed consisted of a welded steel stand on which the two T58 turbines, the main gearbox, the main rotor head, and the associated control systems were mounted. A dynamometer absorbed the power that would normally be supplied to the tail rotor. This was the first application of the PSTB at Sikorsky Aircraft. Subsequent propulsion system test beds have included the tail rotor and the associated drive system and much more sophisticated monitoring installations. However, the test concept and approach were extremely helpful in resolving interface problems and set the pattern for subsequent development programs for other aircraft.

The regenerative test stand for testing intermediate and tail rotor gearboxes began operation shortly after the propulsion system test bed. The main rotor whirl tests started at approximately the same time, followed by the tail rotor whirl tests 2 months later. Tiedown aircraft testing, followed by main transmission regenerative testing, completed the initial test program.

In some instances, the availability of test facilities and test hardware determined which test commenced first. The main gearbox and the main rotor were tested initially on the propulsion system test bed, which was ready for operation first, rather than on the regenerative and whirl test stand, respectively. Since the propulsion system test bed was powered by prototype T58 engines, their limited power capability determined the maximum power settings that were used. The system tests were augmented by design selection and fatigue tests on selected components in an effort to analyze

component performance and simulate the loading during aircraft operation.

RESULTS OF TRANSMISSION SYSTEM TESTING

Main Gearbox

During the H-3 test program, both development and qualification testing was conducted on the main gearbox. The initial qualification testing was conducted on the propulsion system test bed, and on the basis of that testing, a 200-hour TBO was approved. With the advent of the T58-8 engine and its increased power capability of 1,250 horsepower versus 1,050 horsepower for the T58-6, the customer requested that the gearbox be modified to accept this increased capability and to include engine torquemeters within the gearbox. Thus, on the basis of the additional testing that was required for this modified gearbox, a 250-hour TBO was established. Experience on the test stand and with early production aircraft indicated that certain design improvements would be required to meet design objectives, including a higher TBO interval. To accommodate all of the various customer requirements, four basic main gearbox assemblies were designed and tested during the H-3 program. (Numerous minor modifications to these basic gearboxes were made to accommodate particular customer requirements, but such changes have little apparent effect on the overall reliability of the main gearbox.)

A careful review of the H-3 engineering test reports has been made to determine the problems that were encountered during the test programs; the results of this investigation are summarized in Figure 18. Initially, the problems encountered are shown separated into three categories: first, those that could be repaired with the gearbox left installed on the helicopter; second, those malfunctions requiring component removal; and third, those problems that would be detected at the normal gearbox overhaul period but would not cause degradation in performance during normal operation before that time. As can be seen from Figure 18, covering the regenerative, tiedown, and PSTB testing, over one-half of the total malfunctions in the main gearbox test program necessitated removal of the component from the test stands or aircraft. Some interpretation of this data is essential, however, since the test program prior to April 1961 was largely a development program. Although conducted as a qualification program on the initial gearboxes in accordance with Military specification power spectra, the growth potential of the engine necessitated uprating and some redesign of the gearboxes. The early test program also uncovered several problem areas that were developmental in nature. Several malfunctions occurred in the high-speed input section that required changes in manufacturing processes but not in the design of the parts. These malfunctions still appear in Figure 18. Perhaps another viewpoint would be to consider the type of corrective action taken as a result of the malfunctions. Figure 19 provides data in support of this approach for the entire test program on the various versions of the main gearbox. About 63 percent of the malfunctions required design modifications, while changes in manufacturing techniques and material specifications were required to correct 12 percent of the malfunctions. Two percent required new design approaches, although no corrective action other than replacement of parts was required for the other 23 percent of component removals.

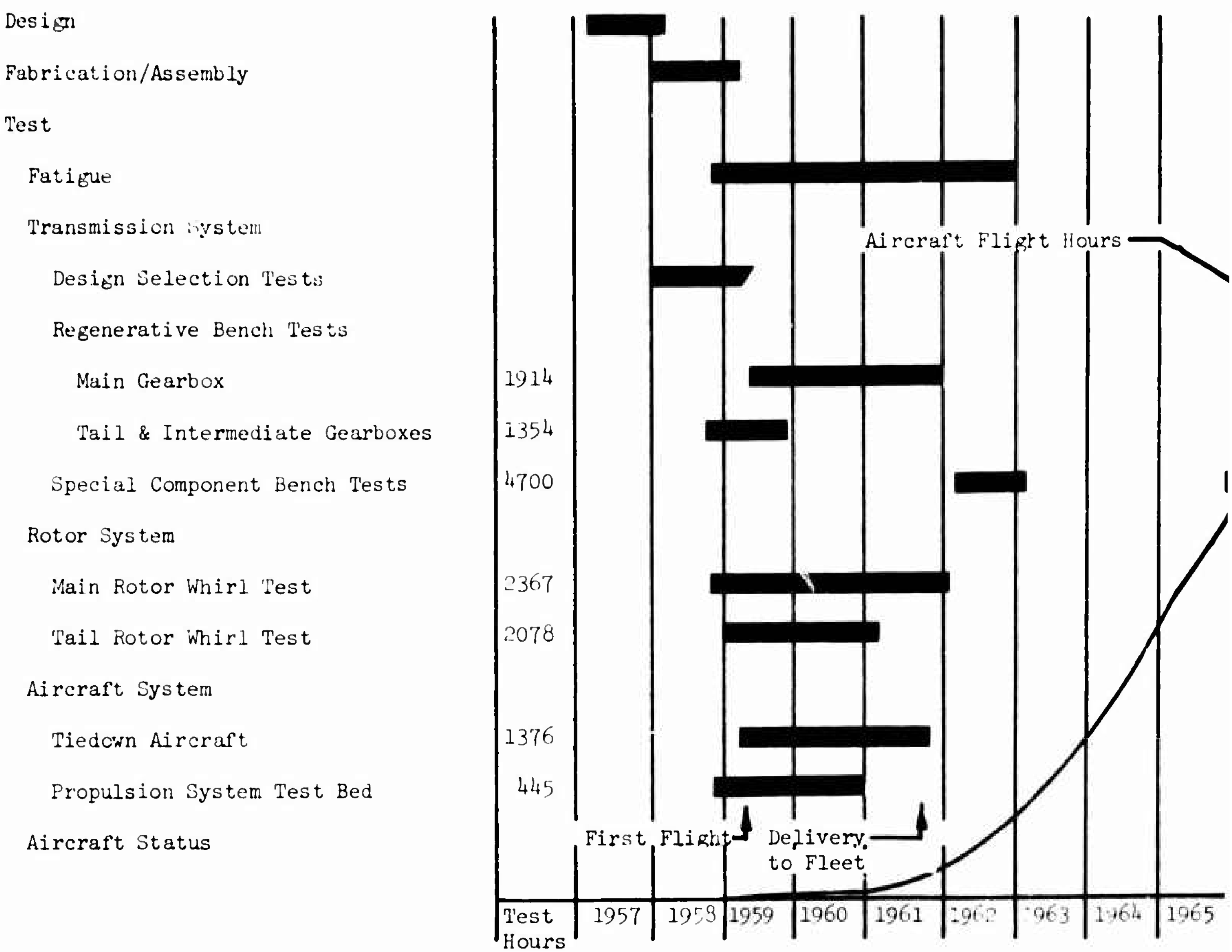
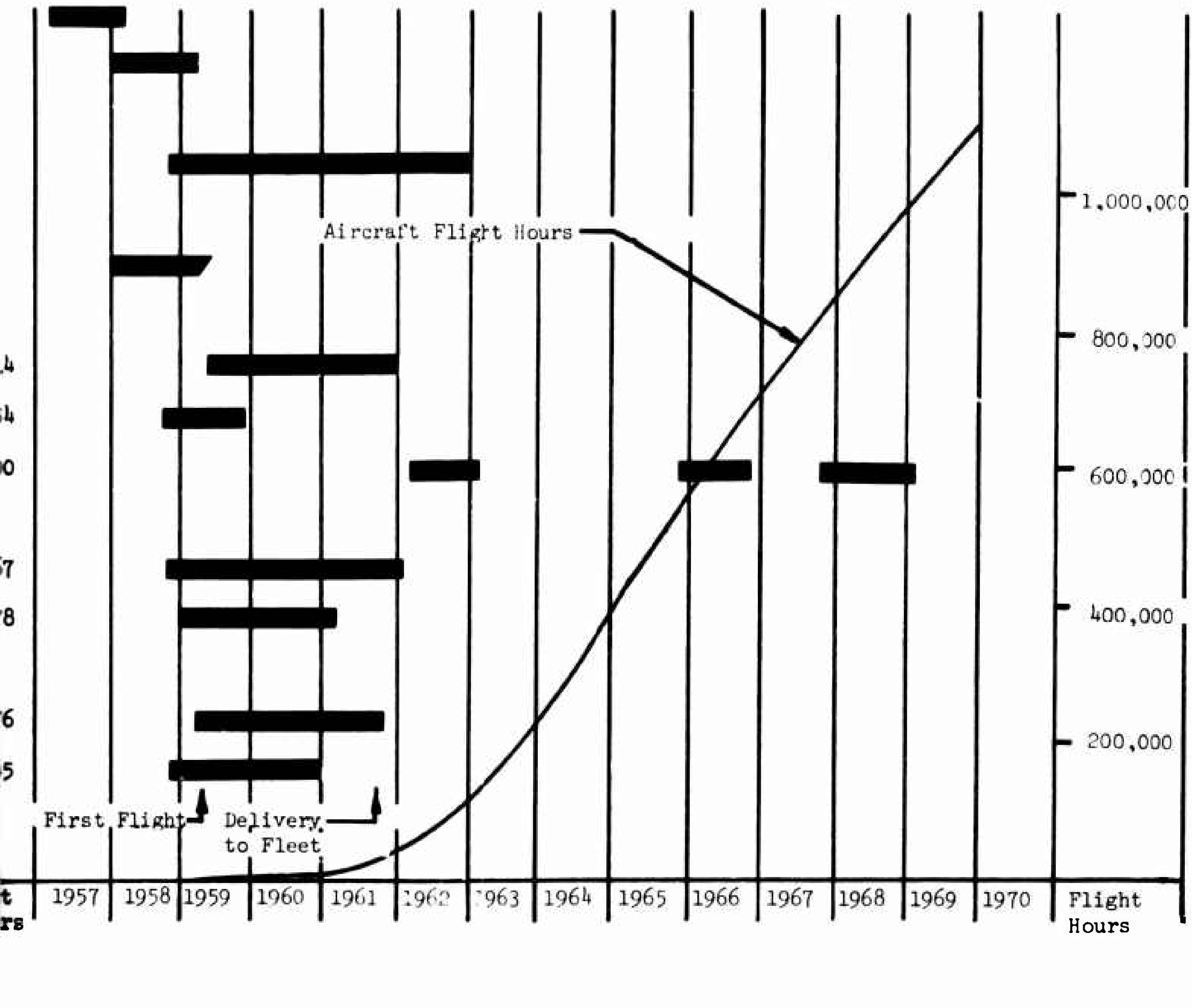


Figure 17. H-3 Program Schedule.



Aircraft Flight Hours
1,000,000
800,000
600,000
400,000
200,000
First Flight
Delivery
to Fleet
1957
1958
1959
1960
1961
1963
1964
1965
1966
1967
1968
1969
1970
Flight
Hours

Schedule.

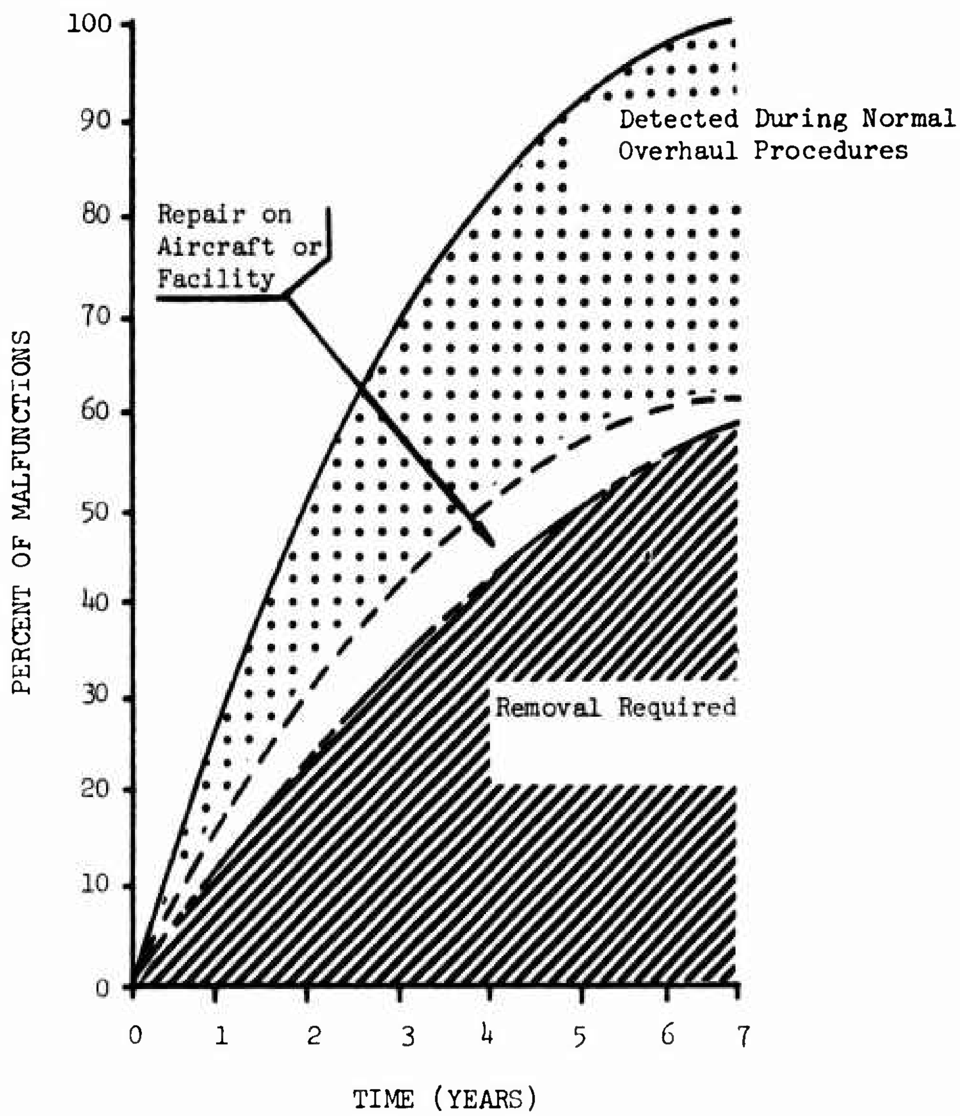


Figure 18. H-3 Main Gearbox Malfunctions by Category.

Preceding page blank

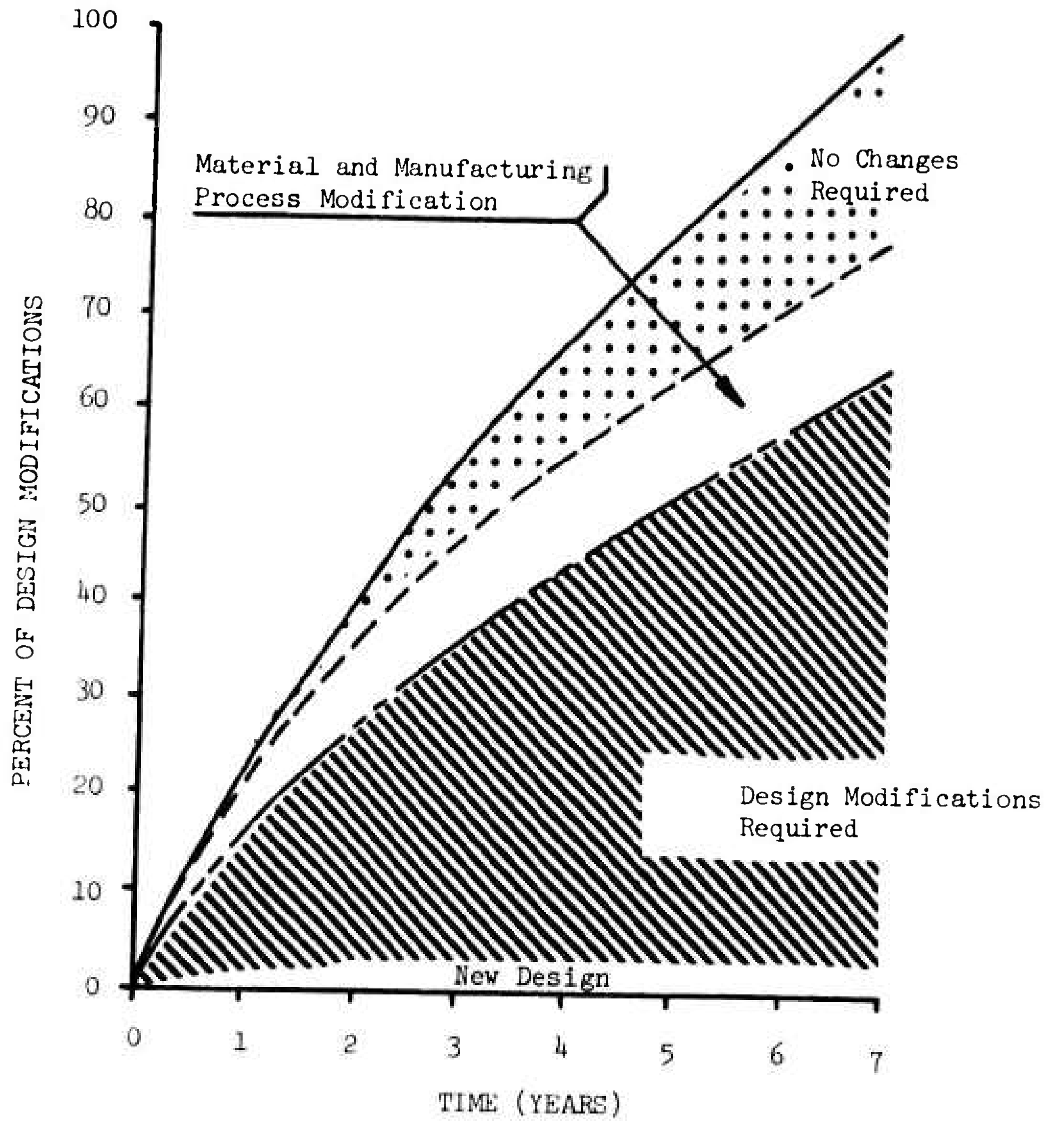


Figure 19. H-3 Main Gearbox Design Modifications During Testing.

Several different testing techniques were employed in this test program. As noted in Figure 17, the main gearbox was developed on a propulsion system test bed, a tiedown aircraft, a regenerative test stand, and the flight aircraft. Each of these tests or types of test has advantages in relation to the overall program, since different testing techniques were employed in each. The malfunctions experienced in the various types of tests on the early gearboxes are strikingly similar, as can be seen from Figures 20, 21, and 22. From these figures, it would appear that inherent reliability will be revealed in any development test program that includes realistic loading simulating operating conditions. But this is not necessarily the case. In fact, simulating service environment and operation is a very involved problem, not usually done during previous test programs. In this H-3 program, the environmental conditions were similar for the propulsion system test bed and the tiedown aircraft. The regenerative test stand was very similar also, except that the temperature of and the moisture in the air were more uniform in the test cell. With the test conditions fairly identical, the similar failures during the test program are not surprising.

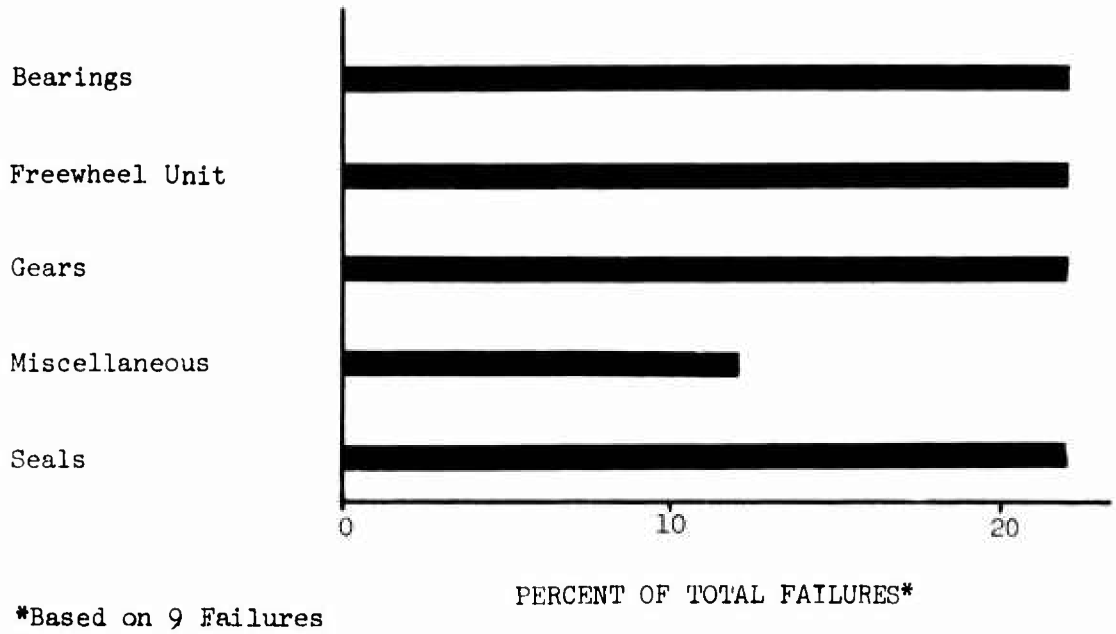
These figures do not reveal the additional interface problems detected and resolved in the integrated system tests. The propulsion system test bed and tiedown tests detect and resolve problems other than just those peculiar to a particular component. These tests defined interface problems with the rotor, control, transmission, and powerplant installations. For example, the H-3 propulsion system test bed provided a means of testing the rotor brake with flight type hardware. Although extensive hardware modifications were required periodically, the lead time provided by the nonaircraft system test allowed flight hardware to be developed without undue delays in the overall program.

Other comparisons are made in Table II, using normalized data with the regenerative bench test as a baseline value of 1.00. From this data it would appear that the propulsion system test bed, where an "iron monster" is used

TABLE II. COMPARATIVE DATA, H-3 MAIN GEARBOX TEST STANDS

Type of Test Stand	Relative Operating Hours per Failure	Relative Operating Hours per Month
Regenerative	1.00	1.00
Tiedown	1.30	0.65
Propulsion System Test Bed	1.85	0.25

for the fuselage and the entire aircraft propulsion system is tested, is the least effective approach to testing. However, it must be remembered that the initial debugging and development effort was accomplished on this test



*Based on 9 Failures

Figure 20. H-3 Main Gearbox Failures, Propulsion System Test Bed.

*Based on 39 Failures

Figure 21. H-3 Main Gearbox Failures, Tiedown Aircraft.

*Based on 118 Failures

Figure 22. H-3 Main Gearbox Failures, Regenerative Test Stand.

stand. When a difficulty was experienced with any portion of the system, the entire test was delayed, producing a low test hour per month value. It would be expected that the most complicated test approach, the tiedown aircraft, would exhibit the lowest test hours per month; however, this is not borne out by the H-3 program. Long delays caused by early malfunctions, lack of backup test hardware, and modifications to the test stand itself lengthened the calendar time required for the propulsion system test bed testing, while the tiedown tests proceeded rather smoothly.

The failures experienced during the test program were classified in yet another manner to determine the modes of failure. This revealed that the failures could be grouped into 12 separate categories as shown in Table III. Although faulty assembly was known to be the reason in 4.3 percent of the cases, it is most likely that this reason caused several additional failures as well, although it is impossible to quantify this item any further.

TABLE III. MODE OF FAILURE SUMMARY, H-3 MAIN GEARBOX

Mode of Failure or Reason for Removal	Percent of Removals **
Contamination	4.3
Faulty Assembly	4.3
Fracture	27.6
Flaking	6.1
Hardware	2.5
High Time*	0.6
Leakage - Seals	1.2
Lubrication System	6.1
Pitting	1.8
Scuffing	3.1
Spalling	28.9
Wear	13.5

*High time removals occurred during the test program because a mandatory retirement time was established for components to allow continuation of the test during redesign and subsequent fabrication.

**Based on 166 Failures

Summarizing the main gearbox test program and the malfunctions experienced on the various test stands, approximately one-half of all failures were bearing failures, as shown in Figure 23. Other primary causes of removal for the more than 5,600 test hours accumulated on the various main gearbox configurations are shown as well. A distribution of these test hours among the various test facilities is shown in Figure 17.

Intermediate and Tail Gearboxes

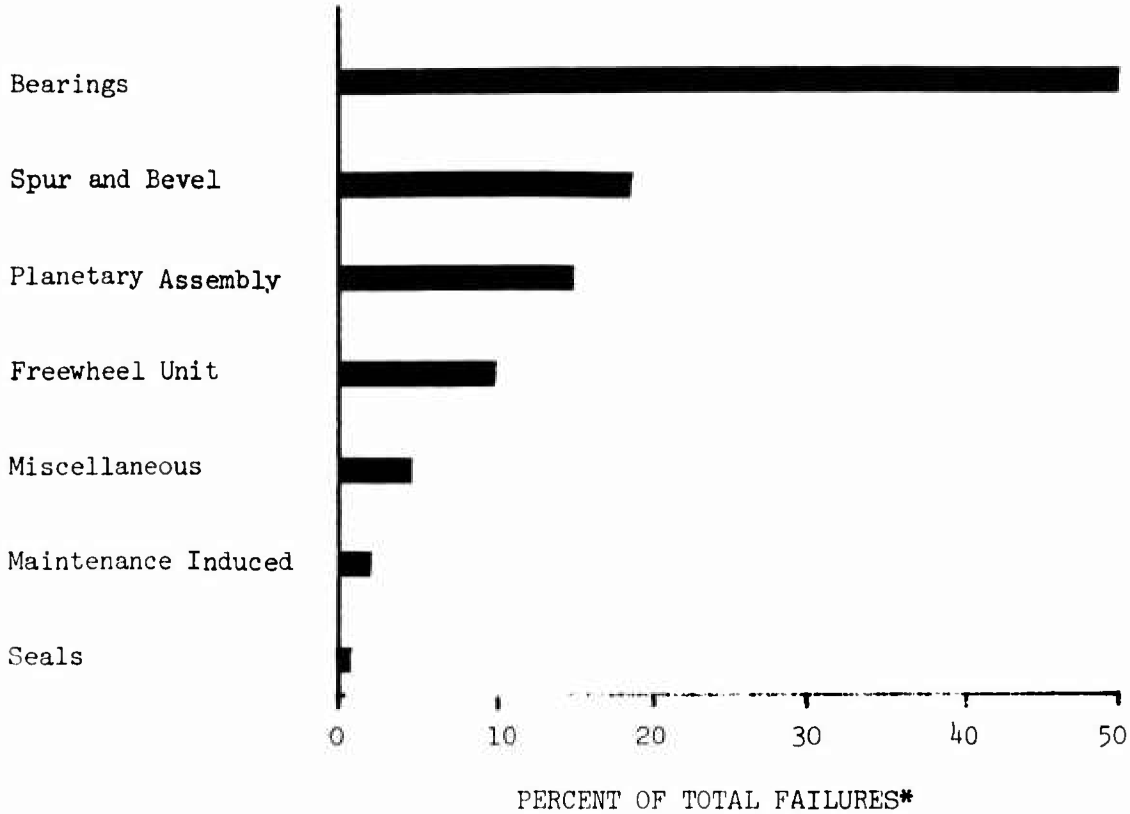
The intermediate and tail gearboxes were subjected to testing in the propulsion system test bed, the tiedown aircraft, and a regenerative test stand, which is shown in Figure 24. These gearboxes, each incorporating a single spiral bevel gear mesh, exhibited excellent reliability during the entire test program. As a result, a 1000-hour TBO was initially approved for both gearboxes. The only difficulty encountered with the intermediate gearbox was a static structural failure of one mounting lug. A few minor problems developed during the tail gearbox test program as well, but only one failure involved safety of flight. That failure involved fracture of the tail rotor pitch beam shaft and was related to experimental manufacturing processes which were changed following subsequent tests in the fatigue laboratory. Other malfunctions experienced during the test program were two spalled tapered roller bearings, one pitted spiral bevel pinion, two worn splines at the tail rotor shaft tail rotor hub interface, and one cracked attachment lug. Comparatively speaking, these were minor problems and did not require extensive redesign or delays in the test program.

DESCRIPTION OF ROTOR SYSTEM TEST PROGRAM

As noted in Figure 17 and in the description of the transmission system test program, the rotor system components were tested on the PSTB, the tiedown and flight aircraft, the main and tail rotor whirl test stands, and in the fatigue laboratory. These several tests were conducted for various reasons and with various operating and loading conditions. While the rotor system was tested as part of the overall dynamic system on the PSTB and the tiedown and flight test aircraft, whirl testing permitted testing the individual rotor systems at accelerated speeds, with the associated increased centrifugal loads, and at accelerated coning and flapping angles over the expected aircraft operation. More than 2300 hours of whirl testing were conducted on the main rotor test stand, while over 2000 hours were accumulated on the tail rotor test stand as shown in Figure 17.

The tail rotor test stand allows precession of the tail rotor about a vertical axis to introduce the effects of flapping on tail rotor performance. Recent modifications to this same stand allow gust loading to be evaluated also. A large ducted fan directs a stream of air onto the tail rotor, and combined with the precessing action, simulates operation in turbulent air.

Individual rotor head components and portions of the rotor blades were tested in the fatigue laboratory to evaluate the designs and verify the



*Based on 166 Failures

Figure 23. H-3 Main Gearbox Failures, All Test Programs.

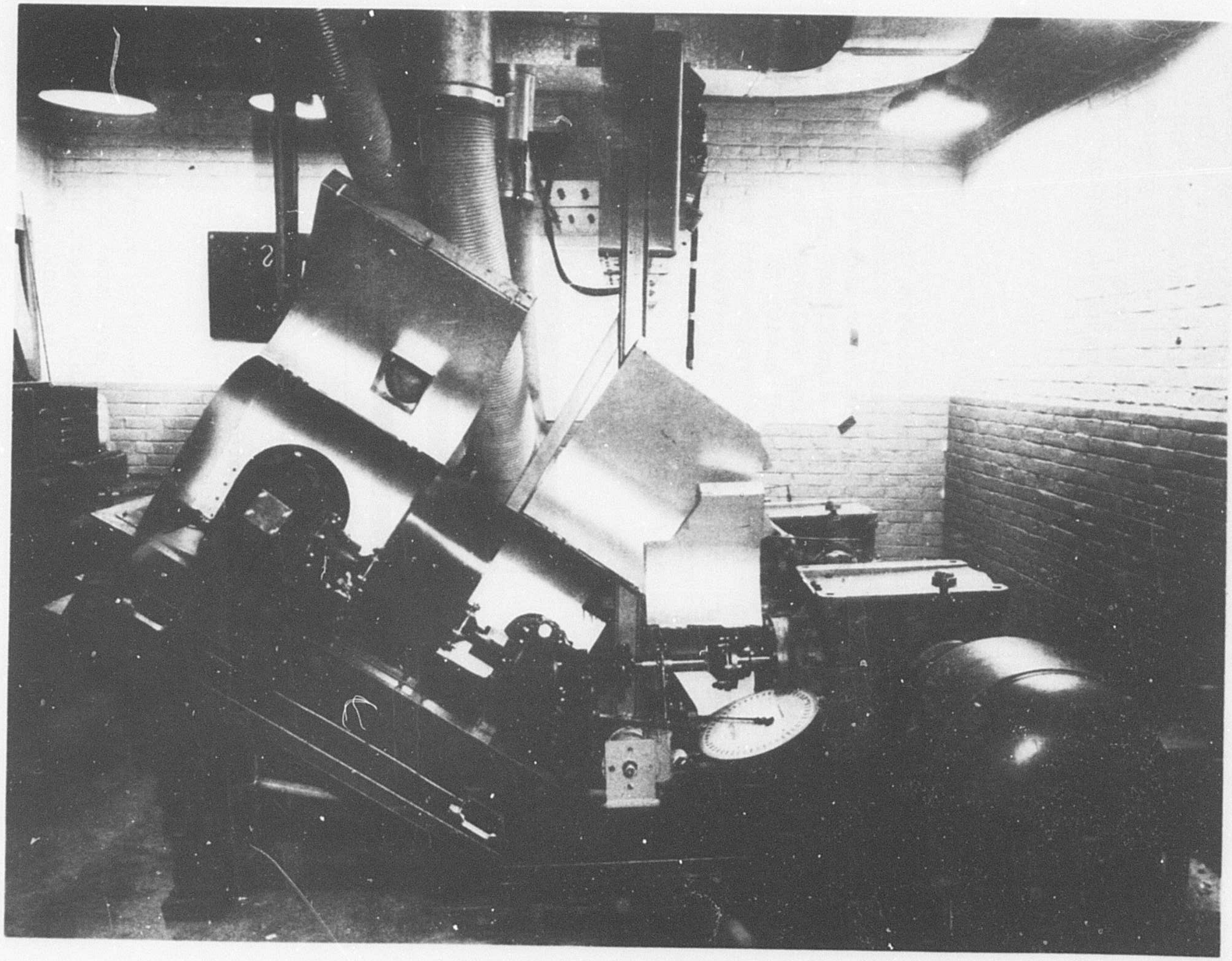


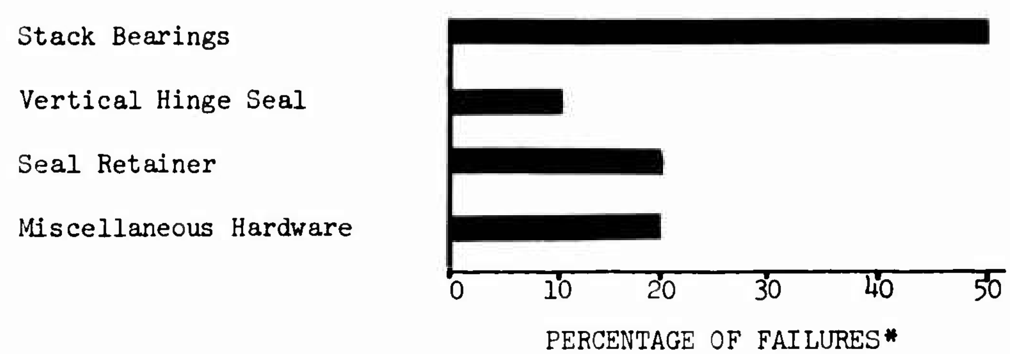
Figure 24. H-3 Tail and Intermediate Gearbox, Regenerative Test Stand.

structural integrity of the various components. This testing is conducted for an entirely different purpose than the other tests in that components are tested to failure or to runout to establish either modes of failure, fatigue strength of the part and safe operating envelope, or an allowable operating interval for a particular component. Thus, failures in the fatigue laboratory are the desired end result, and the more than 350 failures of various rotor head components during the H-3 test program are not indicative of rotor head reliability. As such, they are not included or considered in this study, since their basic purpose was definitive or exploratory in nature.

RESULTS OF ROTOR SYSTEM TESTING

Main Rotor System

Initial testing of the rotor system was coincident with the transmission system testing, since the PSTB was the first test for both systems. Interface and assembly problems were resolved in the rotor and control systems during the early phases of testing and before significant power was absorbed by the rotor system. The ensuing testing evaluated the effects of variations in flapping angle, magnitude, and direction of the resulting thrust vector; vibratory response of the rotor system; and environmental factors such as ice, temperature, and humidity on performance of the rotor system. Figure 25 depicts the types of failures that were experienced during operation of the propulsion system test bed; bearing failures were predominant.



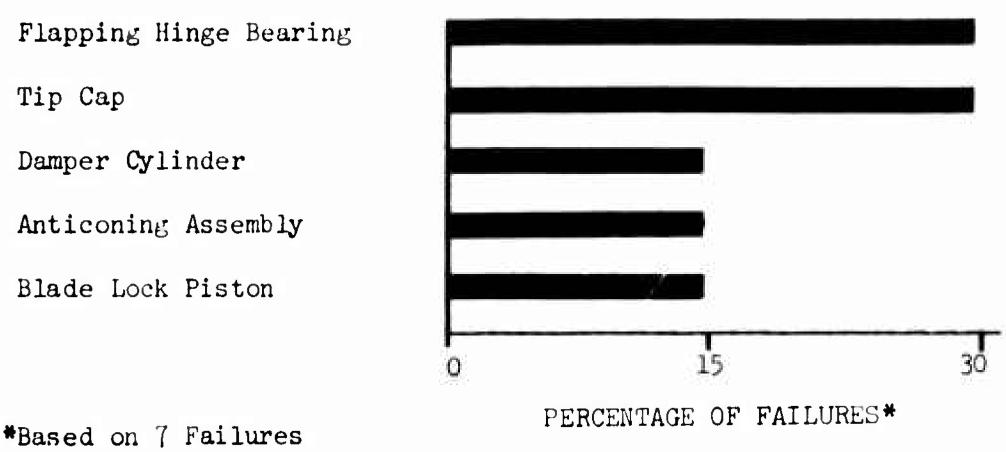
*Based on 10 Failures

Figure 25. H-3 Main Rotor Failures, Propulsion System Test Bed.

Similar testing was conducted on the tiedown aircraft, except that all other dynamic systems of the aircraft were also evaluated concurrently. Although the duration of the test was considerably longer, the testing did not reveal any predominant mode of failure. As shown in Figure 26, various components failed other than those that failed on the PSTB, but these are largely attributed to the longer duration of the testing.

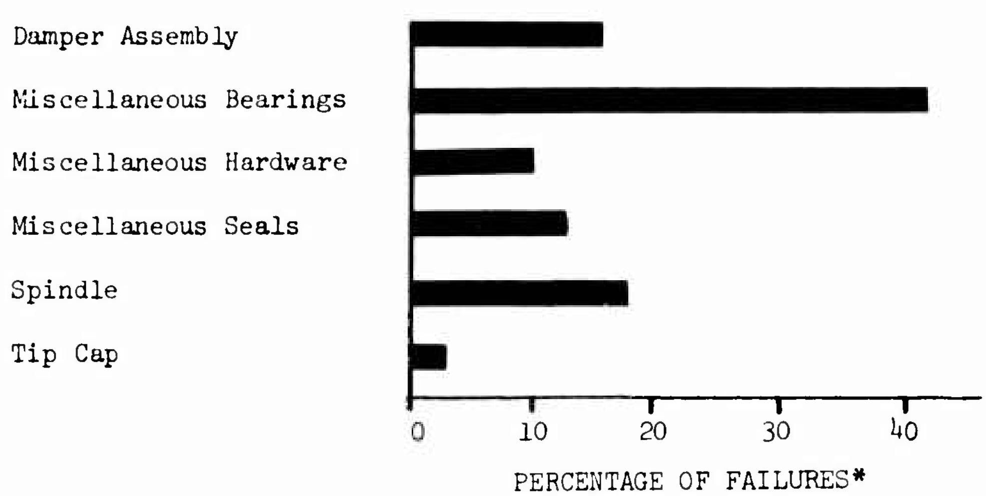
The failures experienced during whirl testing are shown in Figure 27; at

first glance, bearing failures appear to predominate. However, there are different bearing arrangements for each blade in the rotor head and each damper assembly. It follows that the relative failures of three different components are essentially equal. A composite picture of all test stand failures on the main rotor assembly and a list of the various components that required removal are given in Figure 28.



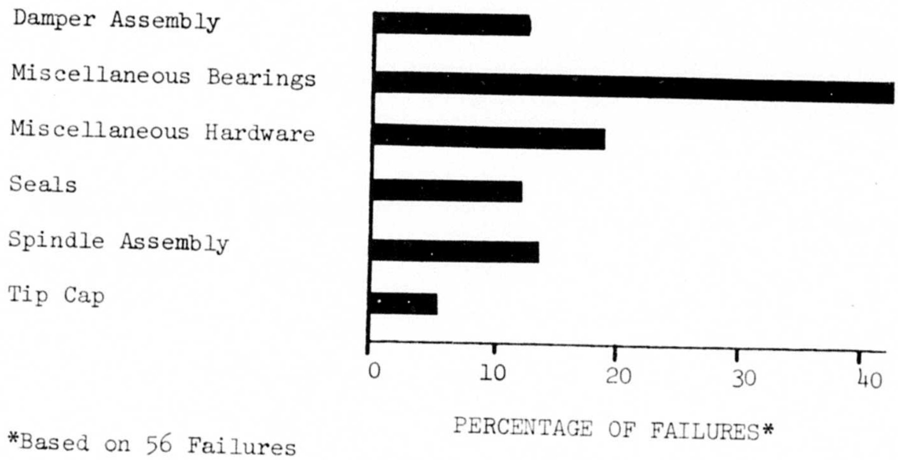
*Based on 7 Failures

Figure 26. H-3 Main Rotor Failures, Tiedown Test Facility.



*Based on 39 Failures

Figure 27. H-3 Main Rotor Failures, 8000-Horsepower Whirl Stand.

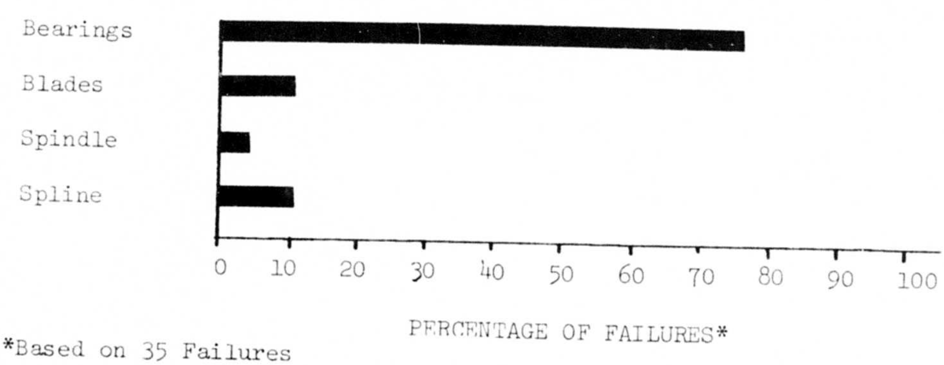


*Based on 56 Failures

Figure 28. H-3 Main Rotor Head Component Failures, All Test Programs (Excluding Laboratory Fatigue Test Programs).

Tail Rotor System

The tail rotor system testing was similar to the main rotor except that the whirl testing was conducted on a tail rotor test stand that permitted precessing of the rotor during operation. Since 80 percent of the failures occurred during whirl testing, and similar modes and types of failures were experienced in the various tests, all failures have been combined and are presented in Figure 29. Even though there are two sets of bearings for each tail rotor blade, this mode of failure predominated during the test program. This test stand is shown in Figure 30.



*Based on 35 Failures

Figure 29. H-3 Tail Rotor Failures, All Test Programs (Excluding Laboratory Fatigue Test Programs).

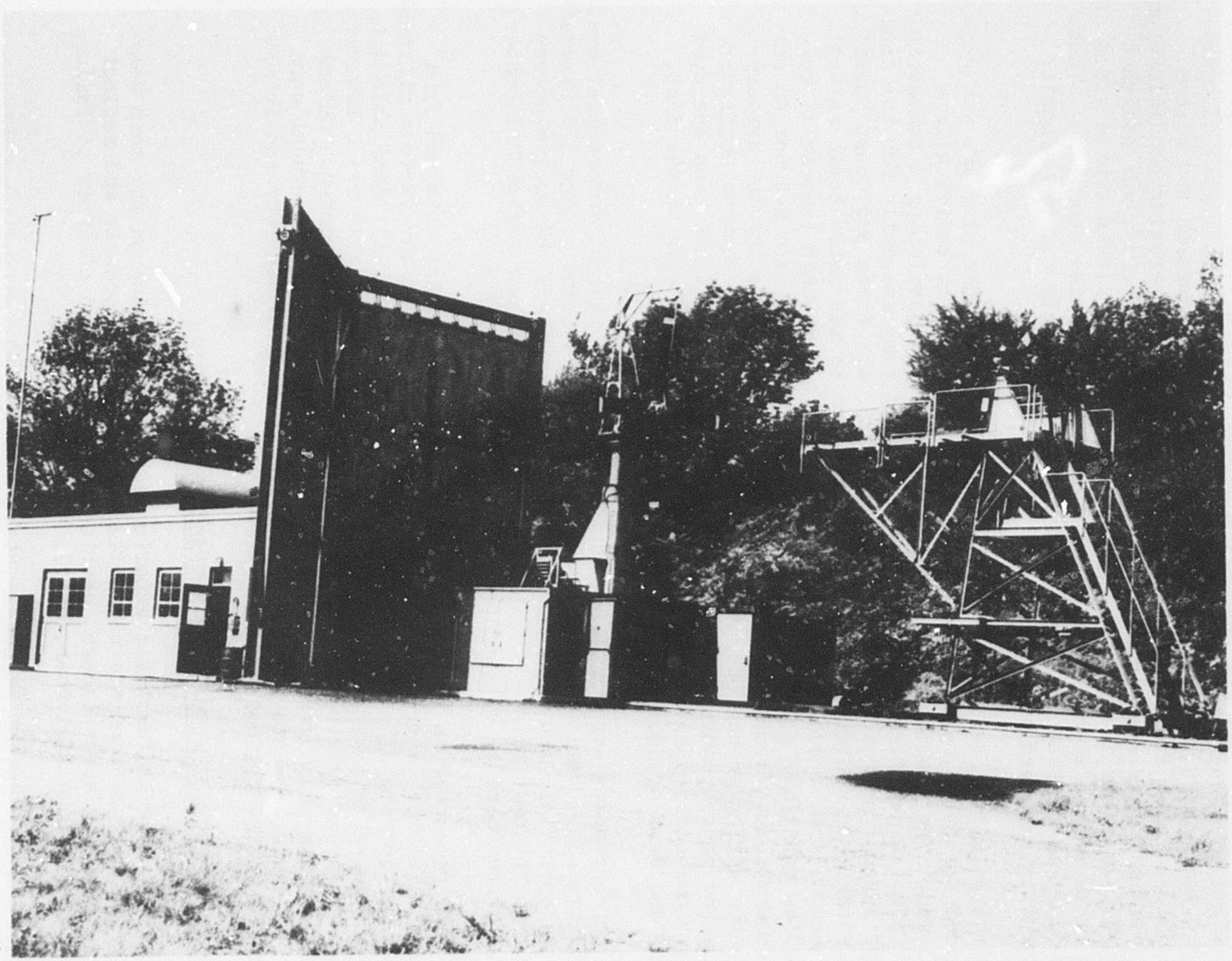


Figure 30. 2000-Horsepower Tail Rotor Test Facility.

SERVICE EXPERIENCE

Extensive use of the H-3 helicopters by various military and commercial users has provided experience in various environments and types of operation. From short, high-power commercial flights to search and rescue missions of much longer duration, widely differing operating conditions and environments have been encountered. The original aircraft was designed with two missions in mind: an antisubmarine mission with a cruise speed of 100 knots and an assault mission with a 135-knot cruise condition. These two missions provided the initial design requirements for the dynamic components reviewed in this study.

After the initial design and development commenced, the aircraft was considered for other operational requirements, and design modifications followed. The fuselage was extended 60 inches in developing a commercial aircraft. A new fuselage with a rear-loading ramp was built for the long-range search and rescue aircraft for the U.S. Air Force and Coast Guard. These aircraft modifications required changes to the drive train as well. Instead of the accessories being driven by the left-hand (number 1) turbine, an auxiliary power unit was mounted behind the main gearbox on one configuration to provide accessory power without operating the primary turbines during ground operation. As a result of the various configurations and corresponding varied operators, the aircraft has been operated in various environments from the cold of arctic operation to the dust, heat, and sand of Southeast Asia.

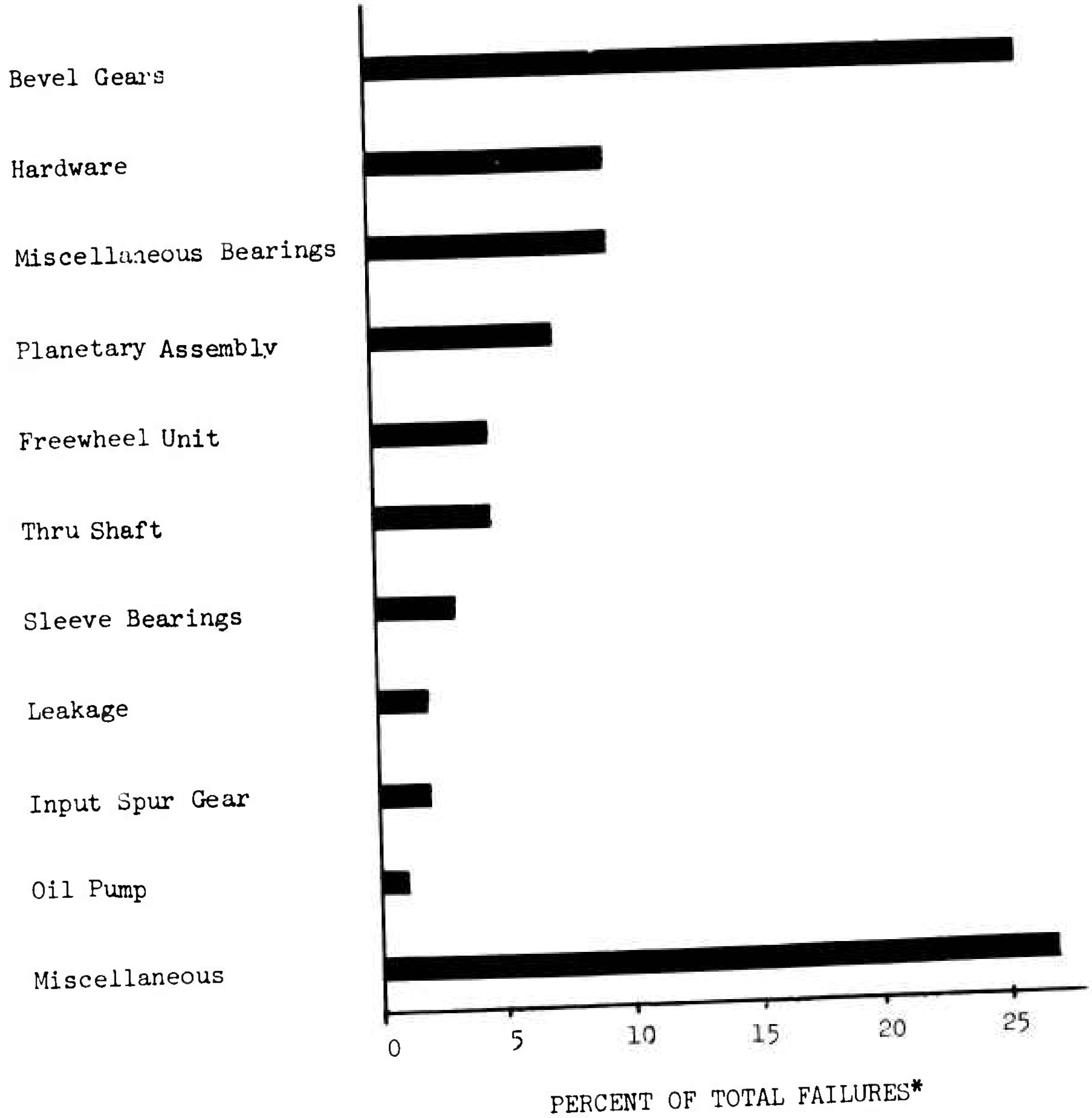
The corresponding service data provide meaningful insight into operational problems, since various modes of operation are included. Over 570 aircraft are in operation, and although the data do not reflect the entire accumulated operating time of over 1,100,000 hours on the H-3 series helicopter, it is representative of single-rotor helicopter operation.

The data presented in the following paragraphs have been obtained from several different sources and types of forms in use by the various military services, commercial customers, and Sikorsky Aircraft. All available data were reviewed to determine the quantities and types of failures. However, certain overhaul and repair work was not conducted at Sikorsky. Unless major problem areas were encountered, information on such overhaul work done at these separate facilities was not relayed to Sikorsky and is not included in the following data.

SERVICE EXPERIENCE WITH THE H-3 TRANSMISSION SYSTEM

Figure 31 shows malfunctions experienced during service on the main gearbox. The malfunctions are classified by various components and reflect various problem areas (gears, bearings, etc.) instead of types of failure (fracture, brinneling, wear, etc.).

The drive shaft installation exhibited exceptional reliability during both test and service. During test, 11 flexible disk couplings experienced deterioration during operation but continued to perform their intended function during test interval, allowing repair following normal shutdown.



*Based on 315 Failures

Figure 31. H-3 Main Gearbox Service Failures.

Service experience with the drive shafting was similar in that the failures were minimal. Only one thrust bearing failure, near the disconnect coupling, and four flexible disk coupling malfunctions have been noted in service. The tail rotor drive shafting consists of five sections of shafting with the end sections joined to the stainless steel tubing by the use of a brazed joint. During service, this connection has failed twice. However, considering the service time and number of components in service, the drive shaft installation has exhibited a very high MTBR.

Service history on the H-3 intermediate and tail gearboxes verified that adequate testing was conducted on the drive train, but environmental tests and seal tests simulating or duplicating service experience were not conducted. As can be seen in Figures 32 and 33, seal leakage accounted for an excessively high percentage of removals for both gearboxes and was the dominant mode of failure.

COMPARISON OF TRANSMISSION SYSTEM TEST AND SERVICE EXPERIENCE

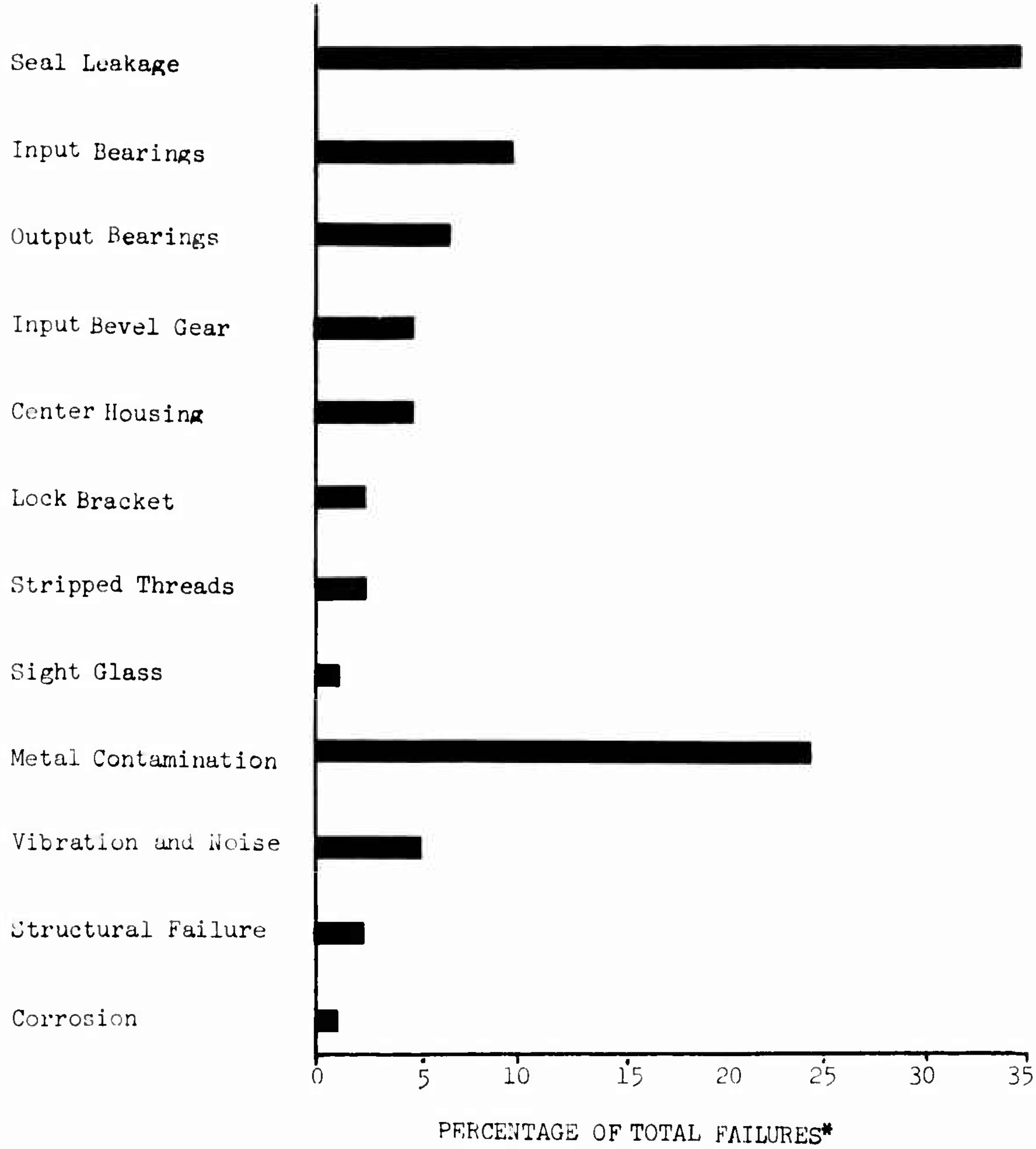
Figure 34 shows that the testing did not simulate actual operation, since apparent disparities exist between the test and field data. Testing and service experience are compared in Table IV. Service data indicated a

TABLE IV. COMPARATIVE FAILURE DATA

Component	Failures During* Test (percent)	Failures During ** Service (percent)
Bearings	49.7	13
Planetary Assembly	14.2	8
Spur and Bevel	17.8	28
Freewheel Unit	9.7	5
Seals	1.1	2
Miscellaneous	7.5	44

*Figure 23
**Figure 31

lower percentage of bearing, planetary, and freewheel unit failures while seals, spur and bevel gearing, and miscellaneous categories exhibited a higher percentage. Remembering that the test program outlined in Figure 17 included much earlier development testing that was used to debug the components, the comparison between the aforementioned accumulated test data and service history failures could be somewhat anticipated.



*Based on 74 Failures

Figure 32. H-3 Intermediate Gearbox Service Failures.

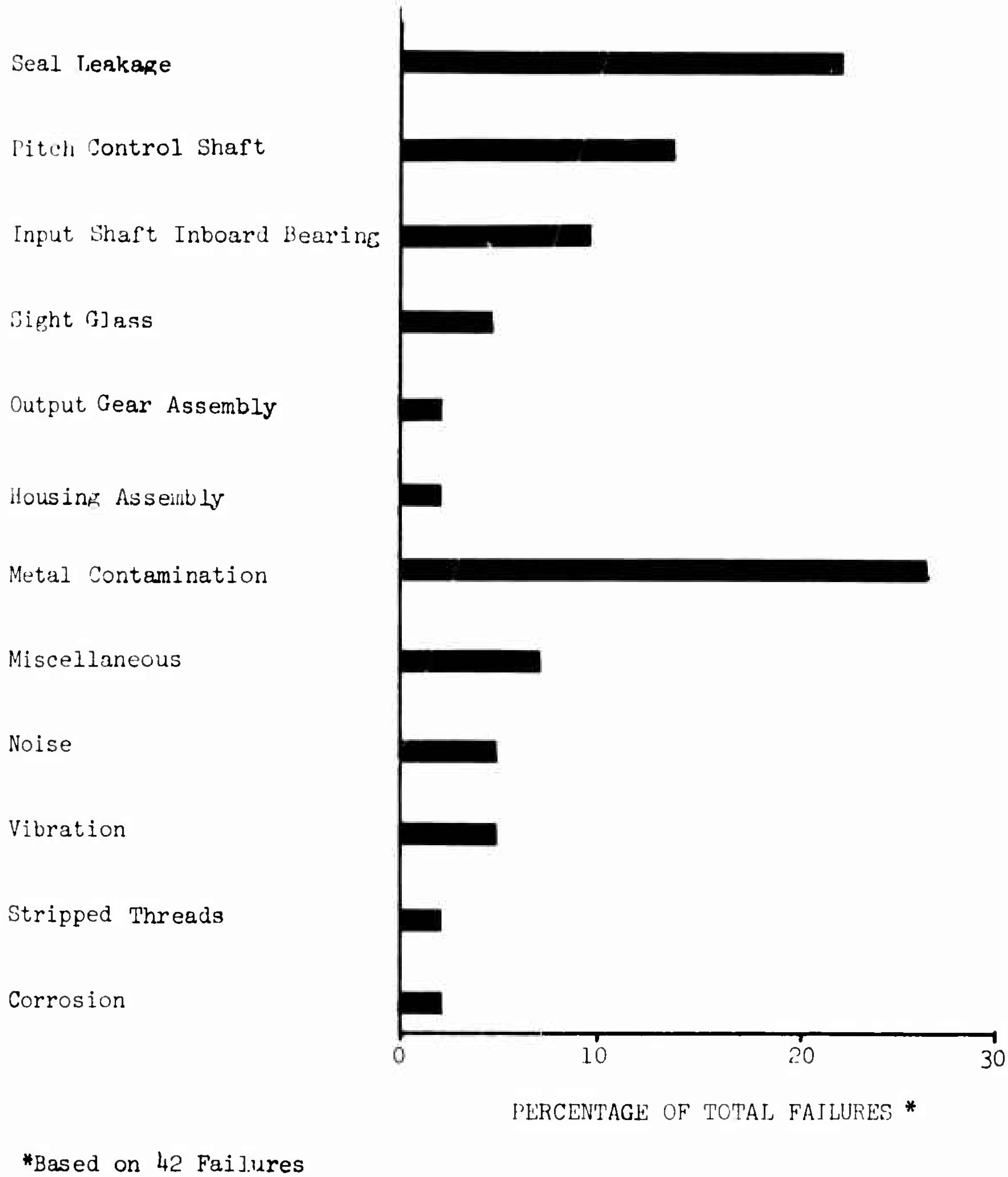


Figure 33. H-3 Tail Gearbox Service Failures.

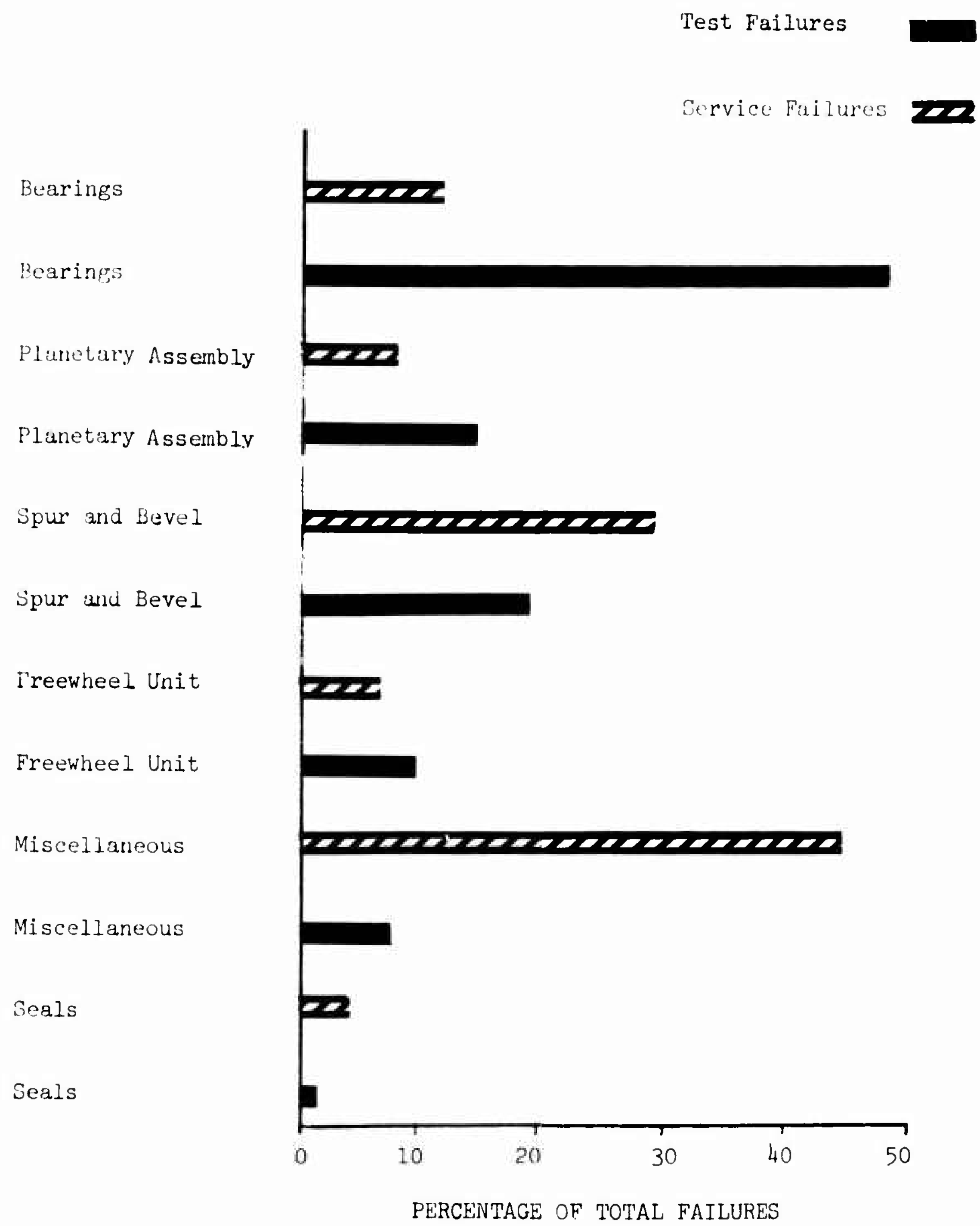


Figure 34. H-3 Main Gearbox, Comparison of Service and Test Failures.

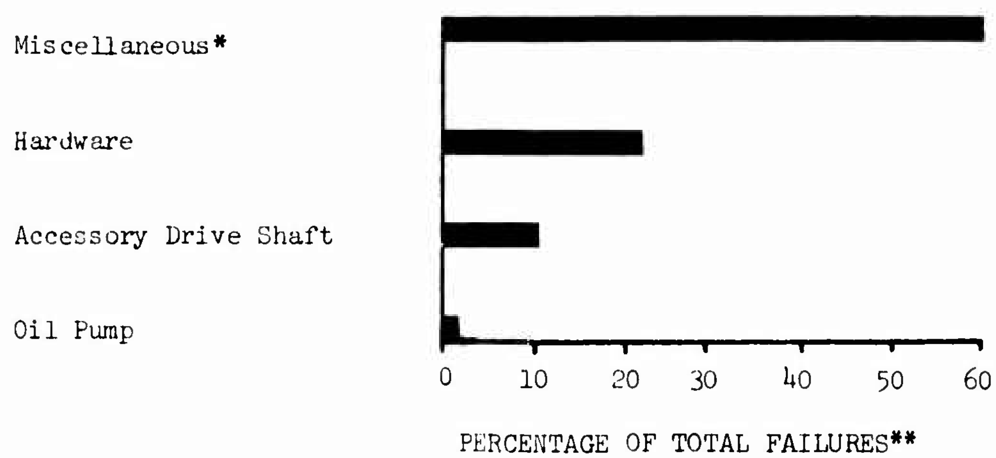
Let us consider the three areas that were responsible for a larger percentage of problems during test than during service - bearings, planetary system, and freewheel unit malfunctions. First, consider bearings. In the main gearbox, there are approximately 45 bearings. Just four sleeve bearings on the high speed input shafts were responsible for one-third of all bearing failures during the test program. However, after initial development, both to the gearbox lubrication system and to the manufacturing processes for the sleeve bearings themselves, this problem was practically eliminated during subsequent operation. Over 50 percent of the bearing failures were caused by spalling. This problem was minimized by several design modifications, including changes in materials, bearing geometry, types and arrangements of bearings, and the lubrication system. The planetary system and the freewheel units are relatively complex assemblies subject to the associated initial development problems. Since the components are so interdependent, initial testing defines the interfaces and the corresponding problem areas; this was true in this H-3 test program. This accounts for the large number of malfunctions experienced during the initial phases of testing.

In contrast, consider service. Instead of a rigorously defined mode of operation with a prescribed power spectrum and environment as in the test stand, aircraft utilization is dependent only upon certain guidelines, red line limitations, and the mission profile that must be flown. Thus, much more varied operating conditions are encountered as soon as the helicopter commences operation. The environment is widely varying, in contrast to the limited test cell conditions. Service may include operating in a sand and dust environment, extreme variations in temperature and humidity, various organic environments, and different loading, and resulting airframe deflections due to peculiar flight conditions. All pilots and operating agencies have practices peculiar to their own operation as well; combined, these environment factors tend to promote a wider variety of problem areas than was experienced in the test cell.

The miscellaneous service problem areas are better defined in Figure 35. Several interesting problem areas appeared only after normal operation commenced. One was the accessory drive shaft, or thru shaft, that supplied power to the accessories from the number one (left) turbine during ground operation. Testing did not simulate flight attitudes, vibration, wear, and the buildup of oil on the inside of the shaft that caused buckling in service. Design modifications corrected this situation and eliminated such malfunctions. Gearbox hardware experienced isolated failures due to its vibratory environment and wear from high time operation. Various minor and singular items appeared, due to such causes as maintenance procedures, corrosion, other primary failures, and contamination, and these required periodic design changes to improve the overall performance of the gearbox.

For the tail and intermediate gearboxes, seal leakage has been the major mode of failure during service operation as shown in Figures 32 and 33. Comparing field experience with the test experience discussed on page 44, one may conclude that we have good correlation on power related failures on such things as bearings and gears but poor correlation on environmentally

affected components such as seals. Had environmental testing, including simulation of component wear, misalignment, and abrasion, been included in the original testing, the service experience could possibly have been better anticipated.



*Metal contamination, noise, high temperature, corrosion, stripped threads, undefined causes.

**Based on 85 failures (Refer to Miscellaneous of Figure 31, 27 percent of 315 = 85)

Figure 35. H-3 Main Gearbox, Miscellaneous Service Failures.

SERVICE EXPERIENCE WITH THE H-3 ROTOR SYSTEM

The initial H-3 series helicopters, developed for operation aboard aircraft carriers, incorporated grease lubricated rotor heads and included automatic blade folding for the main rotor. As shown in Figure 3, the sleeve on rotor heads with automatic blade folding includes a hinged connection on four arms of the rotor head. During blade fold, number one blade, without any hinged provision for folding, is positioned aft, and on each of the

other four blades, two short pins are hydraulically withdrawn from the sleeve-hinge attachment connection, allowing the hinge attachment and blade assembly to pivot about the remaining pin. A major portion of SH-3A rotor head removals was caused by mechanical problems with the blade fold hardware. Damper assembly problems were another major reason for removals on early aircraft, and these two items required design modifications.

Initial service experience revealed that maintenance time on the grease lubricated rotor heads was excessive. The numerous fittings required individual attention; and with human error, there was the attendant possibility that certain fittings would be overlooked and not receive lubrication. Although grease lubricated heads appeared more simple and less involved than oil lubricated counterparts, redesigned rotor heads with oil lubrication were incorporated on subsequent aircraft. This change caused other unanticipated operational problems and changed the primary modes of failure on the rotor heads.

Service experience with both the main and tail rotor blades is summarized in Table V, in which the failures are grouped by component rather than mode of failure. The three primary areas of rotor blade removals are due to pocket, abrasion strip, and tip cap assembly damage.

Data on main rotor head removals are given in Table VI and show that the primary modes of failure were entirely different for the two different assemblies. Although the problems with the blade fold mechanism were corrected on the later rotor heads with oil lubrication, seal leakage became a chronic problem which accounted for two-thirds of all removals. Service data on the tail rotor, given in Table VII, are similar and show that leakage accounted for 61 percent of removals.

Another view of the same failures is provided in Table VIII, in which the modes of failure for the rotor head and for the rotor blades are presented. It can be seen that nearly two-thirds of all blade removals were caused by erosion, abrasion, nonstructural cracks, and bond separation, while oil leakage and bearing wear accounted for over three-quarters of rotor head removals. Removals due to mechanical malfunctions such as blade fold and blade damper assemblies represented a small percentage of all failures.

COMPARISON OF ROTOR SYSTEM TEST AND SERVICE EXPERIENCE

A comparison of the preceding service history with the failures experienced during testing shows rather dramatically the effects of testing. As noted, most of the testing on the main rotor system was conducted on the grease lubricated rotor heads, and the problems detected during those tests were largely developmental in nature. The blade fold mechanism was debugged during test and early service. The major portion of blade testing was concerned with fatigue testing of the spar to verify its structural integrity. Although the initial rotor systems were grease lubricated, the rotor systems were changed to oil lubricated systems following initial service, and a whirl test was conducted to demonstrate that the oil lubricated rotor heads were acceptable for service.

TABLE V. H-3 FIELD SERVICE
ROTOR BLADE FAILURE REMOVAL

MAIN ROTOR BLADE				
Component	Percent* Failure Removals	Mode of Failure	Percent* Failure Removals by Mode	Component
Pockets	26	Cracks	8	
		Bond Separation	13	
		Dented	3	
		Others	2	
Abrasion Strips	25	Erosion	19	Abrasion Strips
		Bond Separation	3	
		Others	3	
Tip Cap Assemblies	24	Cracks and Broken Spot Welds	13	Tip Cap Assemblies
		Loose/Eroded Abrasion Strip	6	
		Others	5	
Miscellaneous	25	$BIM_{(R)}$ Seal Leak	10	Miscellaneous
		Spar Tip Cracks	2	
		Corrosion	3	
		Out of Track	3	
		Others	7	

*Total of 359 Removals = 100%

**Total of 363 Removals = 100%

TABLE V. H-3 FIELD SERVICE
ROTOR BLADE FAILURE REMOVAL DATA

TAIL ROTOR BLADE

ent* ure vals ode	Component	Percent** Failure Removals	Mode of Failure	Percent** Failure Removals by Mode
8				
3				
3				
2				
9	Abrasion Strips	26	Erosion	13
3			Bond Separation	7
3			Others	6
3	Tip Cap Assemblies	26	Erosion	20
			Others	6
6				
5				
0	Miscellaneous	48	Unbalance Water Entrapment	11
2			Cracked Skins	8
3			Loose Trailing Edge Strip	4
3			Lost/Lose Rubber Cap	4
7			F.O.D.	10
			Others	11

TABLE VI. H-3 FIELD SERVICE
MAIN ROTOR HEAD REMOVAL DATA

GREASE LUBRICATED				O	
Component	Percent Failure* Removals	Mode of Failure	Percent Failure* Removals By Mode	Component	Percent Failure** Removals
Blade Fold	45	Frozen Fold Pin	25	Seals	66
		Scored Hinge Bore	17		
		Others	3		
Blade Damper	19	Damper Piston Wear	15		
		Damper Trunnion Wear			
		Others			
Miscellaneous	36	Vibrations	8		
		Corrosion	2	Bearings	13
		Sleeve/Spindle Wear	3		
		Others	23		
				Miscellaneous	21

*Total of 75 Removals

**Total of 256 Removals

Preceding page blank

H-3 FIELD SERVICE
MAIN ROTOR HEAD REMOVAL DATA

OIL LUBRICATED

Component	Percent Failure** Removals	Mode of Failure	Percent Failure** Removals By Mode
Seals	66	Leakage at sleeve spindle & vertical hinge due to:	
		misalignment wear	15
		deflection of parts	16
			35
Bearings	13	Sleeve/Spindle & swashplate bearing removal due to:	
		Wear	10
		Bindings	2
		Others	1
Miscellaneous	21	Swashplate Assy.	
		Wear	3
		Vibrations	6
		Others	12

TABLE VII. H-3 FIELD SERVICE
TAIL ROTOR HEAD REMOVAL DATA

GREASE LUBRICATED

	Percent Failure* Removals	Mode of Failure	Percent Failure* Removals By Mode	Component
Bearings	90	Ratcheting	20	Seals
		Rough	25	
		Binding/Dragging	30	
		Worn (Sleeve & Spindle)	15	
Miscellaneous	10	Seal wear	3	
		Other	7	
				Bearings
				Miscellaneous

*Total of 102 Removals

**Total of 333 Removals

Preceding page blank

H-3 FIELD SERVICE
TAIL ROTOR HEAD REMOVAL DATA

OIL LUBRICATED

Component	Percent Failure** Removals	Mode of Failure	Percent Failure** Removals By Mode
Seals	61	Oil leaking at sleeve/spindle & hub hinge due to:	
		Wear	40
		Misalignment	10
		Deflection of Parts	11
Bearings	25	Ratcheting	11
		Rough/Binding & Dragging (Sleeve & Spindle)	14
Miscellaneous	14	Scored/Worn Sleeve/Spindle Assembly	5
		Vibrations	5
		Other	4

TABLE VIII. MODE OF FAILURE DATA, H-3 ROTOR SYSTEM FIELD SERVICE		
Components	Mode of Failure	Percentage of Total Removals
Main & Tail Rotor Blades*		
	Erosion, Abrasion	32
	Nonstructural Skin Cracks	20
	Bond Separation	16
	Water Entrapment, Corrosion, and BIM Leakage	7
	Others	20
Main & Tail Rotor Heads**		
	Oil Leakage	50
	Worn Bearings	28
	Mechanical Malfunctions	6
	Others	16

*Based on total of 722 removals

**Based on total of 766 removals

Service history indicated that adequate structural tests were conducted on the rotor system components, but adequate testing simulating operating conditions was lacking. For example, only a nominal amount of testing was conducted on the nonstructural components of the main blade during the H-3 development program, possibly because such testing was not required or specified to assure adequacy of the initial design. Testing simulating environmental conditions was very limited, and service history depicts this fact. Failures during actual service were nonstructural in nature and were caused primarily by environmental factors. As shown in Table VIII, the primary modes of rotor blade failures were erosion and abrasion, nonstructural skin cracks, and bond separation.

The rotor head experienced bearing problems in both test and service, but seal failures were the primary mode of failure during actual service. This suggests that adequate testing simulating actual service was not conducted prior to introduction into service. Adequate testing would have detected these failures and allowed design modifications to be introduced before extensive deployment in service. However, such development testing is time consuming and often cannot be done because of unforeseen development problems, the need for immediate remedial action, and contractual requirements. As with the main rotor, structural malfunctions in the tail rotor system were also minimal. The magnitude of bearing removals might also be reduced if the seal failures are likewise reduced, as the bearing failures may be

secondary and the result of seal failures.

EFFECTIVENESS OF TESTING

Transmission System

Considering the test program and the types of tests conducted in developing the H-3 helicopter, the regenerative or back-to-back testing was the most effective in developing the transmission system components in the minimum amount of time. More hours of testing and more failure per hour of testing are achieved in regenerative testing. The H-3 gearboxes were subjected to accelerated spectrum loading that simulated an expected mission profile, and this power simulation appeared to be adequate. The propulsion system test bed should have experienced a higher rate of test hours per month than during the H-3 program, but expediency and the availability of facilities dictated that initial debugging would occur on that stand. However, interface problems within the propulsion system (including engines, rotors, and transmission system) were resolved sooner and allowed the testing on the tiedown test aircraft to proceed more rapidly than would have happened if the tiedown tests had been conducted first. A measure of the effectiveness of main gearbox testing can be obtained from Figure 36. Figure 36 demonstrates the effectiveness of development testing in improving the component (increaseing the MTBF). In this figure the quantity of development test failures (expressed as percentage of total failure during the test) was plotted versus the test duration. This curve was generated from failure data obtained from all levels of testing, including regenerative bench, propulsion test bed, and tiedown tests. These data are tabulated in Appendix III. The slope of this curve at any point represents the instantaneous failure rate for the component at that point. The reciprocal of the slope is then the instantaneous MTBF. It may be observed that, after an initial period during which the slope remains nearly constant, the slope continuously decreases with test time. In other words, the MTBF continuously increases. This topic is pursued in further detail in the section under "EFFECT OF VARYING LEVELS OF RELIABILITY"

To provide better reliability definition prior to introduction into service, a more intensive overall effort would have been required. This would have included a more careful assessment of the effects of environment on design, environmental testing in the test plan, careful failure analysis, and appropriate corrective action where required to meet the overall objectives of the program. Service history on the intermediate and tail gearboxes indicates that environmental tests would have been very timely and cost effective during the initial test program to detect sealing problems before service deployment.

All of the initial gearbox tests used entire gearbox assemblies, and this approach dictated that several interface requirements had to be satisfied simultaneously to allow continuation of a test. Another approach seems more cost effective, in developing the components in a short period of time. As an example, consider the experience on the H-3 main gearbox. As can be seen from the test data presented in Figure 23, unsuccessful gearbox operation resulted from the failure of relatively few parts involving four

distinct areas of the gearbox. A more effective test approach might have been conducted if subassemblies had been tested and developed separately and then combined in one system test. If the failures shown in Figure 23 are regrouped into the associated subassembly, the data in Table IX is obtained. Testing just the first three items in a separate installation could have been accomplished, allowing components responsible for two-thirds of all failures to be developed prior to testing the entire gearbox. Such testing appears to be a cost-effective approach to system testing.

TABLE IX. FAILURES RELATED TO VARIOUS SUBASSEMBLIES

Subassembly	Percentage of Failures
Planetary	28.3
Input Assembly	23.9
Freewheel Units	14.7
Main Bevel Gear Assembly	19.0
Rotor Shaft Bearings	5.5
Miscellaneous	8.6

Rotor System

Adequate simulation of environmental conditions was the dominant factor limiting the effectiveness of rotor system testing. Many of the statements concerning the effectiveness of transmission system testing are also applicable to the rotor system. Structural testing was very effective, but the environmental conditions were not adequately evaluated. Many of these problems could also be eliminated if more subcomponent testing was considered and planned for early in the initial aircraft program. Erosion could be evaluated in several small test stands and in a head and shaft tester for the entire rotor head assembly. Adhesives and bond separation could be evaluated with static shear and peel tests on simple lap joint specimens to select the most promising adhesives. These tests could be followed by push-pull and start-stop fatigue cycling tests on additional lap specimens to determine the effect of stress reversal. The blade specimens would then be fatigue tested at accelerated conditions to determine the most appropriate adhesive. Shim cracks are difficult to eliminate since most occur due to improper handling and carelessness. However, cracks in tip cap attachments can be minimized by careful attention to design refinements and then evaluated by fatigue testing.

Rotor head removal data shows that a careful evaluation of the sealing elements should be conducted before a design is committed to production. Then actual simulation of the expected environments, including loads and

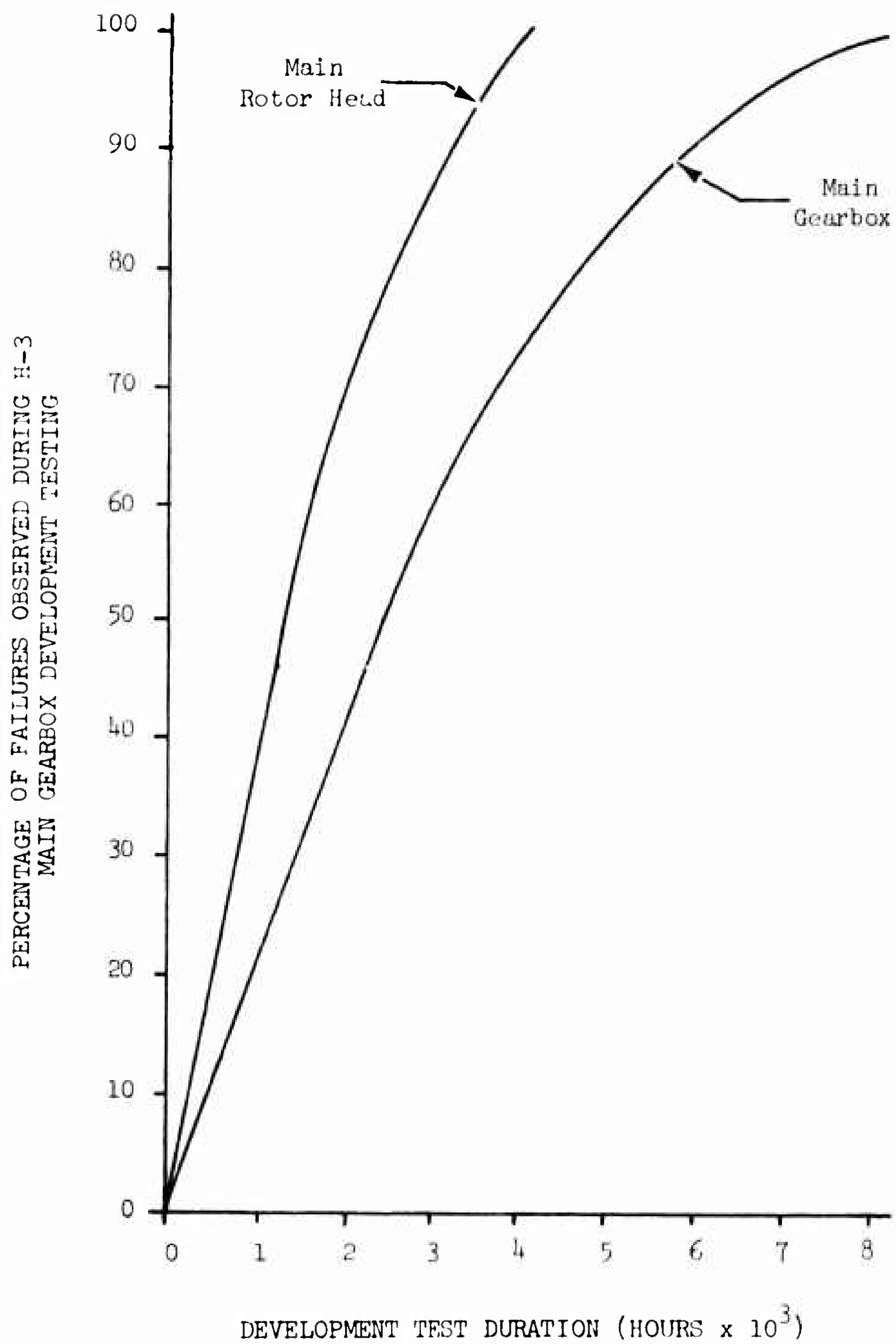


Figure 36. Effectiveness of Development Testing.

deflections, should be included in the test plan leading to rotor head qualification.

Specified operational objectives should be carefully delineated during the design phase of the program, thereby allowing the subsequent test program to proceed and effectively evaluate components that were designed for the same environment. Only in this manner can these subcomponent tests develop and qualify the components in an effective manner.

To illustrate the effectiveness of development testing in improving the H-3 main rotor head, a curve of development test failures versus test duration based on the data of Appendix III was also plotted and presented in Figure 36.

INVESTIGATION OF OTHER TEST TECHNIQUES

The H-3 program reviewed in the preceding pages used test approaches long accepted in the rotary-wing field, such as fatigue, whirl, regenerative, and tiedown tests. These tests use standard test techniques as well, such as applying loads simulating the helicopter environment or somewhat accelerated over the normal operating values, operating for a given number of hours to substantiate a selected service interval, and introducing given deflections in a fatigue test to simulate aircraft operation.

During this study, other test techniques have been investigated in an attempt to determine possible alternate test approaches. Early definition and identification of potential problem areas during testing rather than during subsequent service would minimize lost time due to component malfunction and, correspondingly, reduce maintenance costs drastically since a fewer number of aircraft would be involved should components in service require modification. In addition to providing for early debugging and development work, the ideal test program should then demonstrate the given reliability objectives. This can best be accomplished by an awareness of available testing techniques and their potential applications in a helicopter development program. Possible applicable test techniques have been reviewed and are listed in Table X.

TABLE X. TYPE OF TESTS AND THEIR APPLICABILITY

Test	Applicability
Design Selection Tests	These tests use prototype hardware to evaluate design concepts and techniques. Various alternative solutions to a design problem are fabricated during the preliminary design phase of the aircraft program to determine the final design concept.
Environmental Tests	These tests will expose components to the total anticipated operating environment, including salt spray, water spray, sand and dust, high and low temperature, or any combination of the above. This is of interest in development and qualification tests. The first four environmental conditions relate to structural tests in such areas as corrosion and abrasion fatigue, for which, at present, no Military specifications, standard stress/cycle (S/N) curves or prescribed test procedures exist.

TABLE X. Continued	
Test	**Applicability**
	These tests should be considered because of the adverse effects on endurance limit. Fungus and high and low temperature or various combinations of the above environmental conditions have a marked effect on seal integrity, which is one of the major problem areas during service but is not properly identified during test. As such, environmental conditions must be considered and simulated during qualification testing.
Flow Visualization Tests	Technique can be used where fluid flow is related to a specific mode of failure to determine optimum design configuration. Typical areas where technique can be used include design of tip caps, anti-ice and abrasion strips, rotor blade pockets, dust flow around rotor head and engine compartment and gearbox cooling.
Fractional Factorial Tests	This test technique is applicable to any test having more than one variable, and is a technique in a large group of statistical tests. This reduces the number of test points in an overall test program where several variables interact with unknown effects. The technique can be used to find quantitative results and may present a possible answer to handling the effects of environment on service intervals. For example, conduct a test program with loads, motions, and environmental conditions applied at the same time as opposed to separate tests.
Model and Prototype* Structural Tests	
Model Structural Tests	These tests are useful for comparing different designs, verifying stress analysis, etc. These tests are of primary interest in prototype testing although this does present a possible

TABLE X. Continued

Test	Applicability
	means of substantiating minor structural modifications.
Holographic Tests	This technique is applicable when measurement of "field" of small displacements is required, such as the transmission housing deflection and surface stress pattern. In a large sense the technique lends itself to the investigation of any phenomenon that could produce "interference" properties; for example, vibration analysis.
Photoelastic Tests	These are useful for stress analysis of early prototypes and in development phase testing where the stress pattern is complex and not easily defined. When used in conjunction with a strobe, dynamic stress pattern may be established.
Subsystem Tests	These tests are useful in developing specific portions of an assembly without the test being affected or delayed by unrelated hardware. Examples are testing an output planetary assembly, the high-speed gearing assembly, the freewheel unit, the damper assembly, and the seal arrangements in separate test facilities.
System Tests	This testing is extremely useful during both development and qualification testing. Improved load and motion simulation by automatically programming the various loading conditions allows for spectral tests in which all expected operating conditions are considered. Entire systems can be considered for both development and qualfication testing, allowing for realistic loading several interacting parts and components. Qualification tests performed on total systems offer several distinct advantages, including:

TABLE X. Continued	
Test	Applicability
	System interactions are duplicated. Fatigue tests can be combined with service interval substantiation/demonstration.
	System can be tested in a total environment.
	The number of component tests is reduced, since the overall system is tested as an assembly.
	Certain tests may be highly accelerated, causing "weak-links" to fail early, and thus allowing maximum time to redesign. Such tests uncover modes of failure.
	Although the initial cost of the facility may be higher than subsystem test stands, automated loading reduces manpower and operating costs.

*These tests involve a series of related techniques useful in uncovering structural deficiencies in early designs at relatively little costs.

SUGGESTED APPLICATIONS OF VARIOUS TEST TECHNIQUES

The preceding test techniques can be used in a number of different tests during the development and qualification programs. Their applicability is dependent only upon the type of tests included in the test program and the desired extent and size of the test program. Although several of the following tests were not conducted during the H-3 program, they are useful for development and qualification testing and represent later approaches that should be considered for any future development programs. These various tests are outlined in the following paragraphs.

Rotor Head and Shaft Tests

Two facilities are required: one for the main rotor and one for the tail rotor. The entire rotor head from the inboard portion of the rotor blade to the rotating control system can be tested simultaneously. The facility can be automated, programmed, and monitored. Loads will be independently variable, including displacement and velocity. Facility can include once

per flight (ground-air-ground) loading and normal flight loads, including stop-start loading. Load will include centrifugal force, head moment, two-directional blade bending moment, thrust, torque, control rod loads, damper loads, servo loads, scissors loads, etc. Facility can also include provision for environmental testing, including salt and water spray, dust and sand, humidity, and temperature. This test can provide definitive reliability and structural answers in the areas of rotor head structure, corrosion, abrasion of seals and bearings, integrity of the sealing elements, and lubrication system problems.

Abrasion Strip Tests

Water droplets and/or sand and dust particles will be impinged on typical rotor blade abrasion strip installations simulating expected serious conditions. This test will evaluate potential materials and configurations and will detect excessive wear rates, unbonding of the abrasion strips, and the associated effects on the blade itself.

Special Fatigue Tests

Various rotor head parts will be tested in a manner similar to present component structural tests except that they will be limited to parts that did not fail on the head and shaft tester. These tests will detect reliability problems in primary structural members.

Another group of similar fatigue tests will be useful in evaluating nonstructural rotor head components. As evidenced in the service history, considerable removals are caused by these items, and vibratory loads will be applied to these components, such as tip caps and blade pockets, to induce fatigue failures and detect problems in these areas. Simulated environmental damage to these same components could also be evaluated.

Mode of Failure Tests

These tests can utilize the entire assembly, as an entire gearbox or rotor head, or subassemblies in appropriate test stands. A spectrum of high loads should be applied to locate "weak links" in the system. These accelerated test loads should be selected such that the high loading does not produce different modes of failure in the several components involved than would be experienced under normal operation. Careful choice of loading can preclude the occurrence of such failures.

Scale Model Fatigue Tests of Structural Components

Early design trade-offs can be evaluated in a cost-effective manner by using scale model hardware, fabricated using the actual material, or epoxy for photoelastic testing, and testing in a suitable manner. Changes in the design approach could be made in the program at a much lower cost and before final design was even completed by these smaller components. Fabrication of test specimens would not have to await receipt of the forgings or castings required for the prototype aircraft hardware; model specimens could be fabricated from smaller size raw material.

Seal Tests

These tests can be conducted during early phases of the design and development cycle to allow evaluation of various applications and installations and allow subsequent changes in the components should they be warranted. Fractional factorial test techniques should be used to minimize the test program, eliminate nonessential test parameters, and yet survey potential operating parameters.

The test installations should be adaptable to various sized seals and operating conditions. In addition to environmental simulation, the test parameters should include loading, motions, and wear expected during normal operation. Duplicating the environmental conditions during operation may involve use of special environmental chambers to include the effects of dust, sand, lubricant, and moisture. As evidenced by the service history, such testing is warranted on both rotor head and transmission system components.

Bearing Tests

The above comments on seal tests are also applicable here. The bearing testers should be versatile and permit testing bearings of various sizes and configurations.

Static Stress Pattern Tests

Housing deflections and stresses can be determined on the first or second housing to ensure structural adequacy or define areas requiring redesign. These tests would augment the gear deflection tests and provide assurance of the structural integrity of the housing.

Transmission Subassembly Component Tests

Isolation of the various transmission subassemblies allows development of the individual components with a minimum number of interfaces. The facility should provide close simulation with the subsequent aircraft installation, including component attitude, lubrication, and mounting arrangements. The possible types of subassemblies that can be tested in such an installation, include input gearing, freewheel units, accessory drive clutches, and coupling and drive shaft installations.

TEST PROGRAM TRADE-OFF STUDIES

INTRODUCTION

In accordance with the contract requirements, trade-off studies and analysis of various combinations of testing techniques applicable to the development phase of a helicopter program were made.

Two trade-offs were performed. The first considered a concurrent development and demonstration test schedule and compared this with a schedule of sequential or nonconcurrent development and demonstration testing. In the concurrent test program all levels of testing are initiated at about the same time, whereas in the sequential or nonconcurrent test program the various levels of testing occur successively. To conduct this study, a plan was selected from among four that were structured and reviewed. The plan was geared to a 500-hour MTBR at a confidence level of 60 percent and is used in the first portion of the trade-off studies section in order to make it more readily understood. The second trade-off study then takes into account variations in MTBR and confidence levels starting at the paragraph titled "EFFECT OF VARYING LEVELS OF RELIABILITY". A general description of all four plans is presented in Appendix I.

The second study provides a tool to evaluate the impact of development and demonstration testing on cost with varying levels of reliability and confidence. A family of curves relating cost to program duration is provided. These curves differentiate development testing from demonstration testing for each of three levels of reliability and three degrees of confidence.

To minimize the overall program costs, development, production, spares, and retrofit, the most effective means of demonstration testing of the dynamic components is at the system level on ground tests prior to the system going into the field. The very premise of reliability is early detection and correction of malfunction. It is recognized that the complete aircraft in the field is closest to operational use. However, it is also recognized that factors of time and cost become prohibitive once the system is operational in the field.

No accelerated loading is considered during demonstration in these trade-off studies for two reasons. First, accelerated loading has different effects on the various components, such as gears, bearings, and seals. Second, the effect of accelerated testing upon the various test programs being considered is relatively equal.

TYPES OF TESTS

Fatigue Tests

In the following test plans, the fatigue tests of flight critical components are treated in a manner different from all other tests. The critical nature of these components and their impact on the safety of the aircraft and its personnel,and the design requirements for fatigue are not specified as an MTBR but as a service life based on conservative fatigue allowables

which give us a structural reliability order of magnitude greater than any MTBR that is to be considered in this report.

Fatigue test components are subjected to highly accelerated loading levels to define the

Critical modes of fracture, including their detectability and propagation characteristics.

Mean crack initiation strengths well in excess of aircraft operating load levels.

Mean strength of the material which is then reduced by factors of 30 percent for steel and 39 percent for aluminum and magnesium and used as fatigue working strengths.

The flight stress spectrum is then applied to this data using an analysis to calculate time to crack initiation. Wherever practical, designs incorporate fail-safe concepts via redundant load paths and/or crack detection devices. The adequacy of these design provisions is verified during the component system fatigue test.

System Tests

The system tests described in these plans are subjected to applied spectra of loads, powers, speeds, and motion. The spectra are designed to duplicate the dynamic conditions and environment under which the components will function. For the purpose of the time and cost estimates in these comparative evaluations, the demonstration test spectra is applied at levels experienced during service and is not accelerated. Later on in this report, the advantages of accelerated testing are discussed.

Development and Demonstration Testing

Development testing is conducted to debug the design. Redesigns are made and modifications incorporated to improve the design help to approach the desired reliability goal more rapidly. The type of development testing is more important than the duration. The development test plan must be designed to uncover as many failure modes as possible as early as possible.

Demonstration testing as presented in this report is essentially synonymous with, but more extensive than, that testing which had previously been referred to as qualification testing. Currently, helicopter dynamic system qualification testing is carried out in accordance with specifications such as MIL-T-8679. This specification sets forth the minimum duration of "must pass testing" that must be completed to qualify the components. Demonstration testing referred to in this report is distinguished by the fact that the test is quantified by rigorous statistical methods which examine not only the duration of testing but the risk that the population will not behave in accordance with the samples tested as well. In both qualification testing and demonstration testing, unlike the development testing, the design is held fixed, and the test is used to prove that the design will

either pass or fail the preestablished goals.

It must be recognized that it is essential to have a fairly extensive development program prior to demonstration if a meaningful demonstration test is to be conducted.

TEST PLANS

Initially four different test plans, each of which represents a slightly different approach to the problem of developing and qualifying the dynamic components of the helicopter, were considered. From these plans, detailed in Appendix I, evolved the basic test program to be evaluated for demonstration of the various MTBR and confidence levels.

The test plan selected for purposes of the concurrent and sequential tradeoff is geared to detect as many modes of failure and developmental problems as early as possible in the program and to demonstrate an MTBR of 500 hours at a 60-percent confidence level. The demonstration test in this program is performed on a combination of PSTB (propulsion system test bed) and the tiedown aircraft where a total of 1600 hours will be accomplished with two failures per system permitted. The test plan is presented in two stages. Figure 38 presents the work breakdown structure of the program. Although this figure looks like the usual organization chart, it is not. In this figure, level has no significance. Each test task in this figure has several other tasks to a single test requirement. For example, in Figure 37, total system reliability demonstration consists of system development and system qualification, while system qualification requires qualification of systems A and B.

The second presentation of the test plan, Figure 39, shows the interdependence of the various program events on each other. Circles represent events in time (usually the start or end of a phase), and the lines that connect the circles present the activity that leads from one event to another. An event cannot occur until all activities (lines) leading to that event are complete. The charts are read from left to right.

The test program was designed for both concurrent and noncurrent or sequential execution of each test phase. The concurrent test plan, Figure 40, was developed for a total program duration to initial fleet delivery of four years. In this plan the component and system development tests are initiated at essentially the same point in the program schedule consistent with component availability and aircraft safety (i.e., approximately 50 hours on PSTB is completed prior to first flight, and at least a two-to-one ground-to-flight test ratio is maintained thereafter).

In the nonconcurrent or sequential test plan, Figure 41, system tests are initiated only after successful completion of some (approximately 50 hours) duration in the component of lower level system tests.

Test Duration

The duration of the individual tests of the concurrent and sequential test

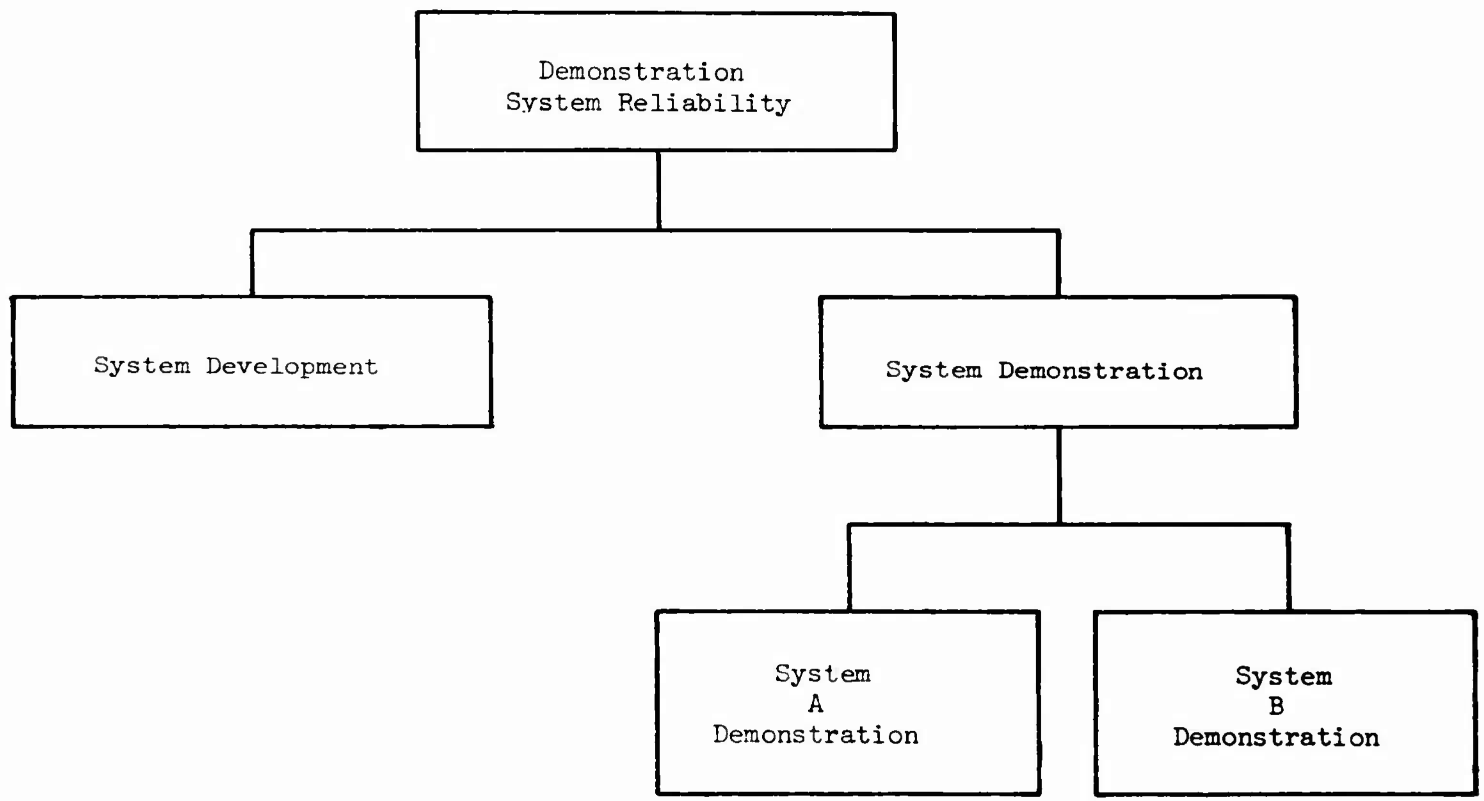


Figure 37. Typical Work Breakdown Structure.

programs of Figures 40 and 41 are presented in Table XI. Included in this table are the number of development and demonstration test hours as well as an estimate of calendar time in months.

Component Requirements

The component requirements to demonstrate an MTBR of 500 hours at a confidence level of 60 percent for the test plan described on the previous pages are shown in Table XI. The extent to which this MTBR can be predicted by individual failure mode is shown in Table XVII in Appendix I.

Program Costs

The relative costs of the concurrent and sequential test plans of Figures 40 and 41 are shown in Figure 42. It should be noted that two gearbox regenerative bench test facilities will be needed for the concurrent program (Figure 40) to accomplish the required amount of development work within the program schedule and prior to initiating the demonstration test phase. The program costs presented are based on data accumulated during the H-3 program as described by Figure 17. These costs, which have been adjusted to 1971 values and presented for each type of test in Table XII, are approximate. The costs of Figure 42 are based on the following:

1. Aircraft gross weight is in the 15,000-to-20,000-pound range.
2. Aircraft dynamic component design costs are not included.
3. Main and tail rotor whirl stands are available at contractor's facility.

The relation between test hours and test costs in dollars per hour is shown in Figures 43 and 44. Two typical types of tests, main rotor whirl and gearbox regenerative testing, are shown. The cost per hour of testing decreases with test duration.

PROGRAM FLEXIBILITY

Consider the probability of detecting a new mode of failure in a given test plan as a function of elapsed time. Initially, during development test the probability is high. With each passing day the probability decreases, being substantially lower during qualification or demonstration testing and ideally being very low during field usage of the machines. Experience has shown, however, that where the test environment represents only a partial approximation of the true operating environment, the probability of detecting new modes of failure during deployment in the field is substantially increased. If the original testing fully duplicates service environments, the probability of detecting failures will increase in the development phase and increase in the field usage phase. This is shown pictorially in a hypothetical plot of probability of detecting a mode of failure versus elapsed time (Figure 45).

Now consider the cost of implementing a change in a given machine as a

TABLE XI. TEST DURATION, COMPONENT REQUIREMENTS
500-HOUR, 60- PERCENT CONFIDENCE TEST PLA

	Test Duration				
	No. of Month*	Total Hours	Development Hours	Demonstration Hours	Quantit
Design Selection	9-10	A/R	A/R	N/A	A/R
Fatigue					
Experimental Stress Analysis	20	A/R	A/R	N/A	A/R
Structural Component Test	20	2000	2000	N/A	4-6
Main Rotor Hub and Shaft	18	2500	2500	N/A	2
Tail Rotor Hub and Shaft		2500	2500	N/A	2
Transmission					
Bearing and Seal	6	500	500	0	A/R
Special Component Bench Test	8	1000	1000	0	
No-Load Lube	1	50	50	0	
Gear Development	1	50	50	0	
Mode of Failure	6	700	700	0	2
Regenerative Bench Test	6	1200	1200	0	2
Rotor					
Main Rotor Whirl Test	5	50	N/A	N/A	1
Tail Rotor Whirl Test	4	50	N/A	N/A	1
Aircraft System					
Power System Test Bed	14	1000	400	600	2
Tiedown	12	1000	0	1000	

*See Figures 40 and 41

RATION, COMPONENT REQUIREMENTS
R, 60- PERCENT CONFIDENCE TEST PLAN

tion opment rs	Demonstration Hours	Component Requirements Quantity	Component	Type	Remarks
/R	N/A	A/R	A/R	Model Prototype	Development Test
/R	N/A	A/R	A/R	Model Prototype	
00	N/A	4-6	Main and Tail Rotor Hub and Control Components		Structural Fatigue Substantiation
00	N/A	2	Main Rotor Head Installation	Prototype	Development Test Replace and Modify as Required
00	N/A	2	Tail Rotor Head Installation	Prototype	Development Test Replace and Modify as Required
500	0	A/R	Critical Transmission Bearing and Seals and Associated Hardware	Production Prototype	
000	0				
50	0		Transmission	Production Prototype	Development Tests Replace and Modify as Required
50	0				
700	0	2	Plus 2 Dummies of Each Type		
200	0	2	Transmission	Production Prototype	
/A	N/A	1	Main Rotor Head Installation		Performance Stress and Motion
/A	N/A	1	Tail Rotor Head Installation		Performance Stress and Motion
400	600	2	Complete Power Train		
0	1000				

TABLE XII. TEST COSTS

Test[5]	Average Hours/Month Development	Demonstration	Facility Costs[1]	Unit C Development
Main Rotor Head and Shaft	140	200	$280,000	$60,000 per
Tail Rotor Head and Shaft	140	200	$120,000	$30,000 per
Rotor Structural Components[7]	N/A	N/A	$650,000	$ 5,000 per
Main Rotor Whirl Tests[2]	10	N/A	$170,000	$ 400 per
Tail Rotor Whirl Tests[2]	12	N/A	$120,000	$ 300 per
Gear Endurance Regenerative Bench Test	100	N/A	$800,000	$ 200 per
Gearbox Mode of Failure Regenerative Bench Test	50	N/A	-[3]	$ 500 per
Propulsion System Test Bed	50	100	$700,000	$ 1,400 per
Tiedown Test[6]	50	100	$200,000	-
Flight Test[6]	18	N/A	N/A	$10,000 per

(1) All costs are approximate and are based on 1971 dollars. These are planning figures onl quotation purposes.

(2) Facility already exists. Costs are only for setup (including adaptation of test compone

(3) The mode of failure testing, no-load lubrication, gear development, and endurance all us regenerative bench test facility.

(4) Excludes cost of components to be tested.

(5) Design selection tests, experimental stress analysis, and bearing and seal tests are usu programs and have comparatively little effect on overall dynamic component reliability d and have not been included in these data.

(6) Aircraft for the Tiedown Test and Flight Test are bailed aircraft, and engines for the P GFAE equipment; their costs are not included in these data.

(7) The design requirements for fatigue are not specified as an MTBR but as a service life b allowables which give us a structure reliability order of magnitude greater than any MTB

Preceding page blank

TABLE XII. TEST COSTS

erage Hours/Month		Facility	Unit Cost of Test (1) (4)	
pment	Demonstration	Costs (1)	Development	Demonstration
0	200	$280,000	$60,000 per specimen	$45,000 per specimen
0	200	$120,000	$30,000 per specimen	$22,000 per specimen
A	N/A	$650,000	$ 5,000 per test hour	-
10	N/A	$170,000	$ 400 per test hour	-
12	N/A	$120,000	$ 300 per test hour	-
0	N/A	$800,000	$ 200 per test hour	-
50	N/A	- (3)	$ 500 per test hour	-
50	100	$700,000	$ 1,400 per test hour	$700 per test hour
50	100	$200,000	-	$800 per test hour
18	N/A	N/A	$10,000 per test hour	

are based on 1971 dollars. These are planning figures only and are not be be used for

ts are only for setup (including adaptation of test component) and instrumentation.

no-load lubrication, gear development, and endurance all use the same ($800,000)
lty.

be tested.

imental stress analysis, and bearing and seal tests are usually selective small test
ly little effect on overall dynamic component reliability development program costs,
these data.

and Flight Test are bailed aircraft, and engines for the Power System Test Bed are
re not included in these data.

atigue are not specified as an MTBR but as a service life based on conservative fatigue
ructure reliability order of magnitude greater than any MTBR considered in this report.

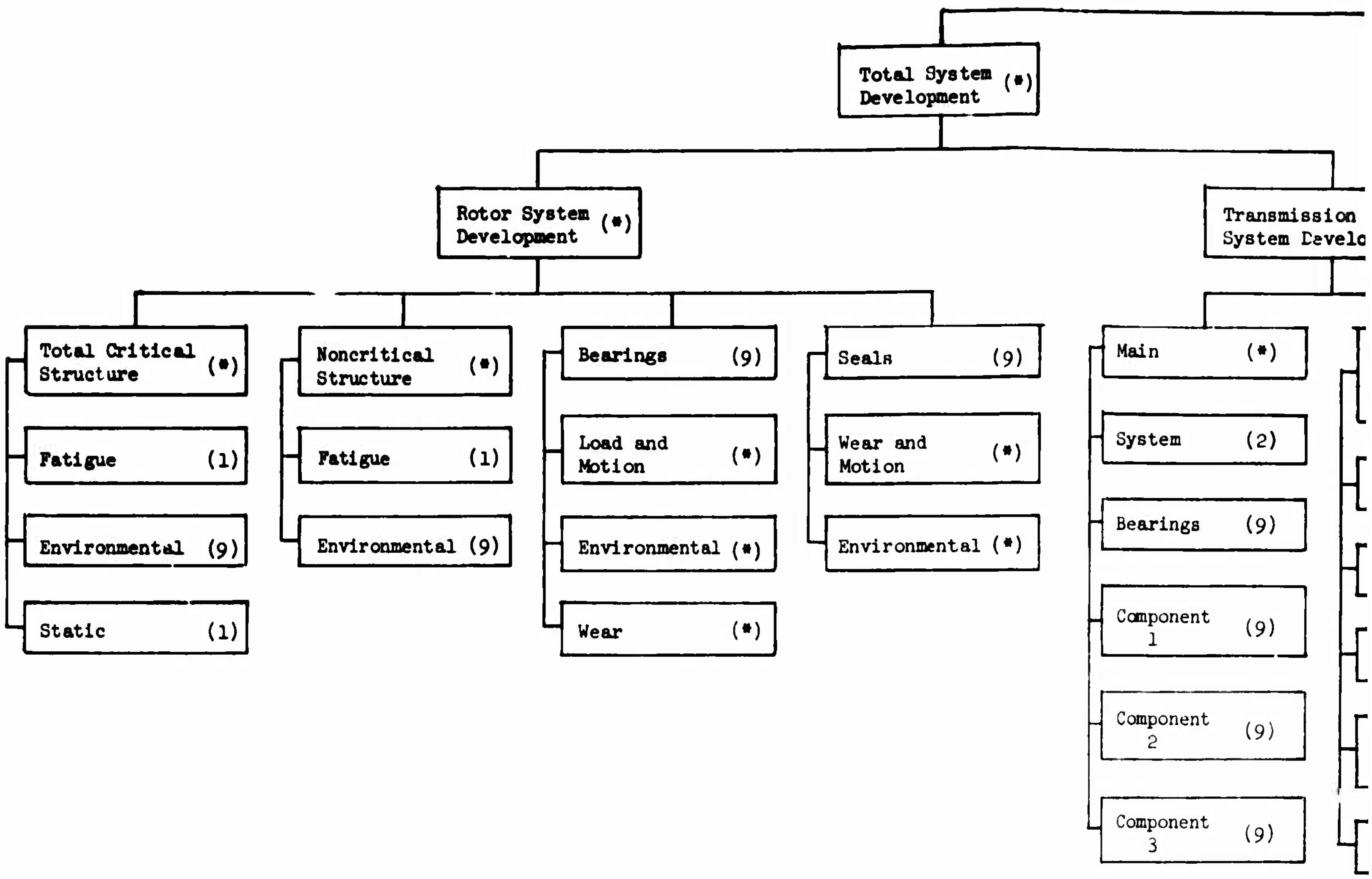
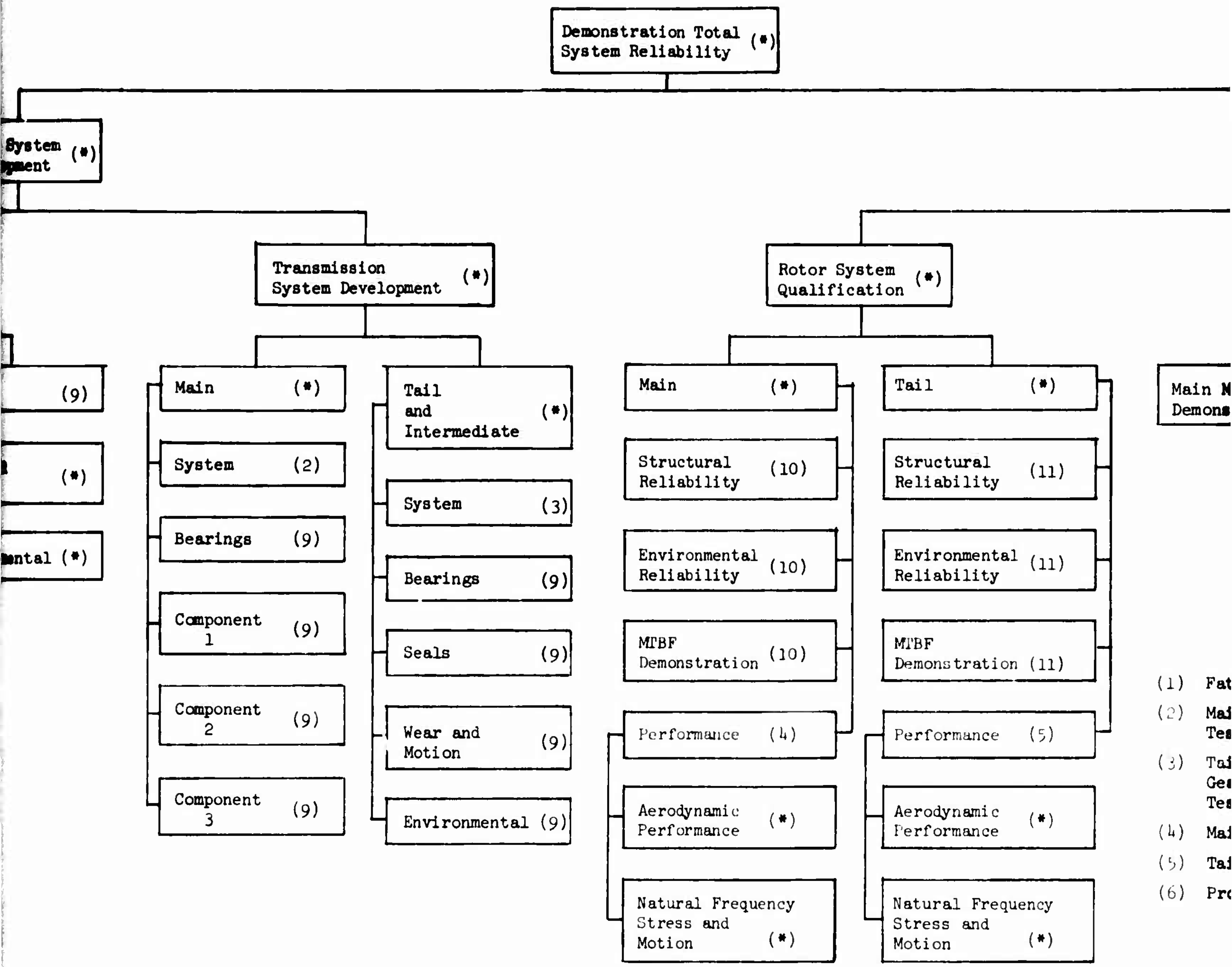


Figure 38. Plan 1, Selected Test Program.

Preceding page blank



Demonstration Total System Reliability (*)
System pment (*)
(9)
(*)
ntal (*)
Transmission System Development (*)
Main (*)
System (2)
Bearings (9)
Component 1 (9)
Component 2 (9)
Component 3 (9)
Tail and Intermediate (*)
System (3)
Bearings (9)
Seals (9)
Wear and Motion (9)
Environmental (9)
Rotor System Qualification (*)
Main (*)
Structural Reliability (10)
Environmental Reliability (10)
MTBF Demonstration (10)
Performance (4)
Aerodynamic Performance (*)
Natural Frequency Stress and Motion (*)
Tail (*)
Structural Reliability (11)
Environmental Reliability (11)
MTBF Demonstration (11)
Performance (5)
Aerodynamic Performance (*)
Natural Frequency Stress and Motion (*)
Main M Demons
(1) Fat
(2) Mai Tes
(3) Tai Ge Tes
(4) Mai
(5) Tai
(6) Pro

Total System Qualification (*)

...stem ...ation (*)

Tail (*)

Structural Reliability (11)

Environmental Reliability (11)

MTBF Demonstration (11)

Performance (5)

Aerodynamic Performance (*)

Natural Frequency Stress and Motion (*)

Transmission System Qualification (*)

Main MTBF Demonstration (2)

Tail and Intermediate Transmission MTBF Demonstration (3)

Intergrated System MTBF Demonstration (7)

<u>Test Facility Legend</u>

(1) Fatigue Tester

(2) Main Gearbox Regenerative Test Stand

(3) Tail and Intermediate Gearbox Regenerative Test Stand

(4) Main Rotor Whirl Test Stand

(5) Tail Rotor Whirl Test Stand

(6) Propulsion System Test Bed

(7) Tiedown Aircraft

(8) Flight Aircraft

(9) Small Scale Development Test Equipment

(10) Main Rotor Head and Shaft Tester

(11) Tail Rotor Head and Shaft Tester

(*) The facility number(s) is (are) the same as the one(s) for the adjacent block(s) tying into it.

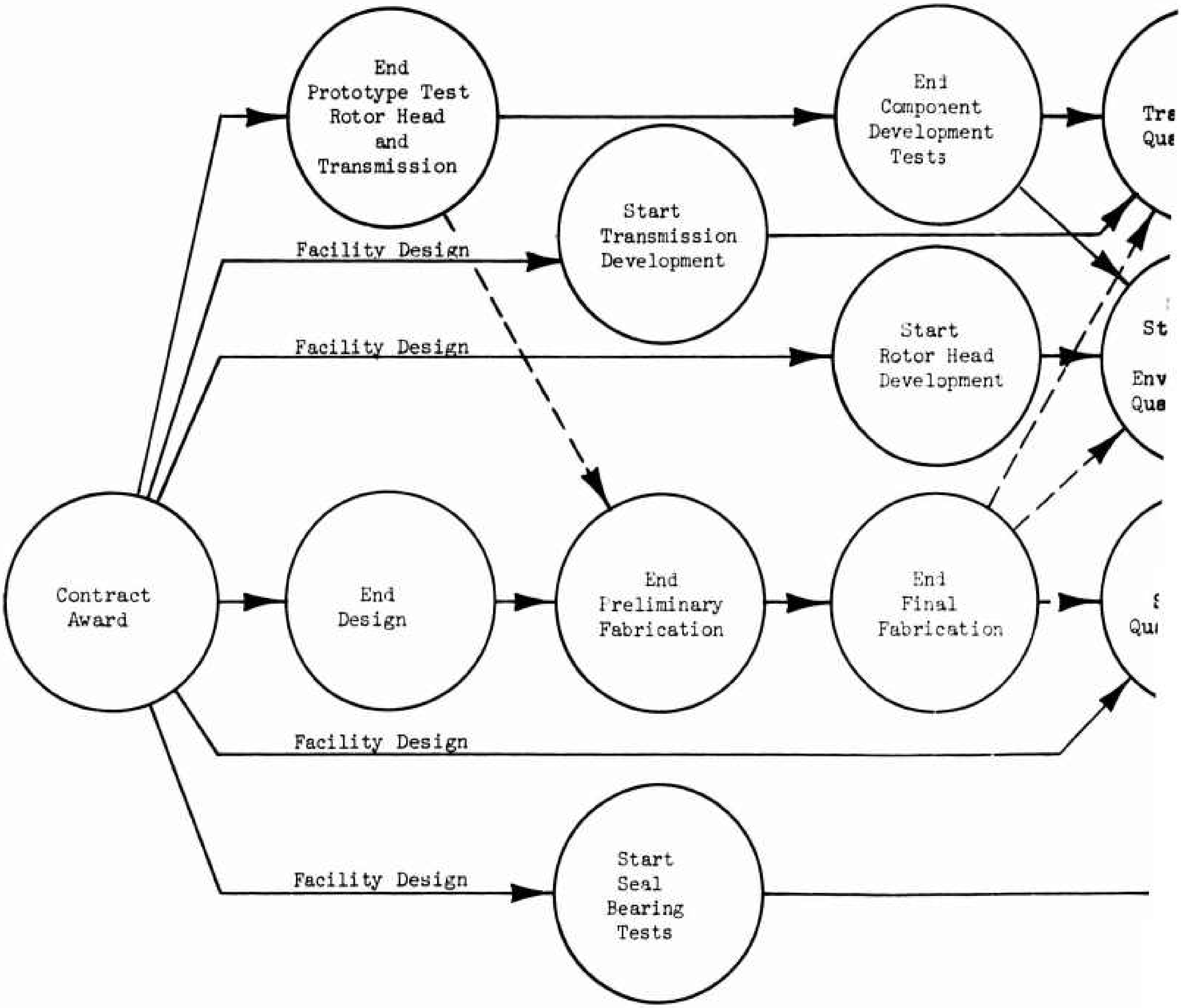
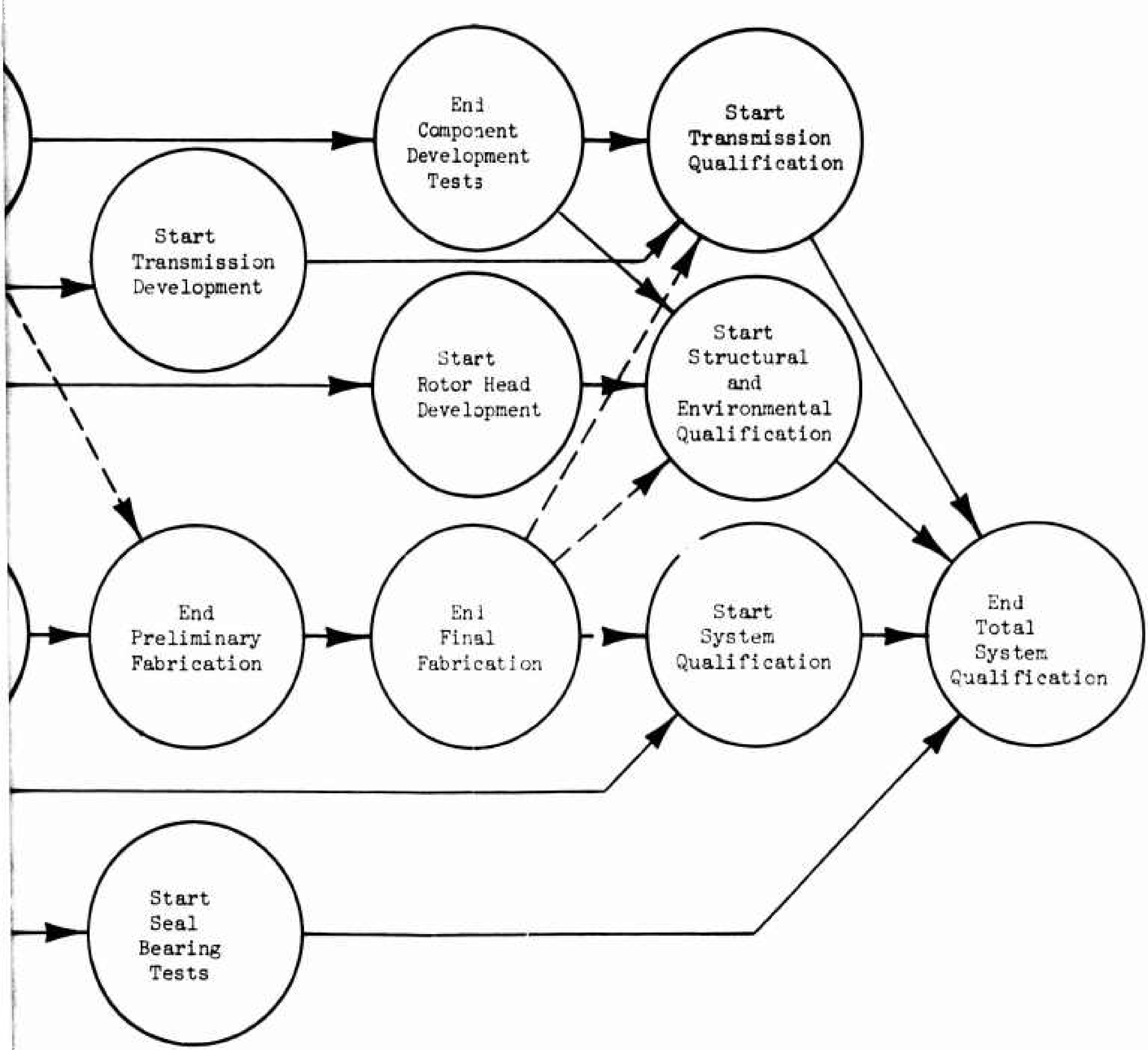


Figure 39. Plan 1, Selected Test Program Flow Chart.

Preceding page blank



Program Flow Chart.

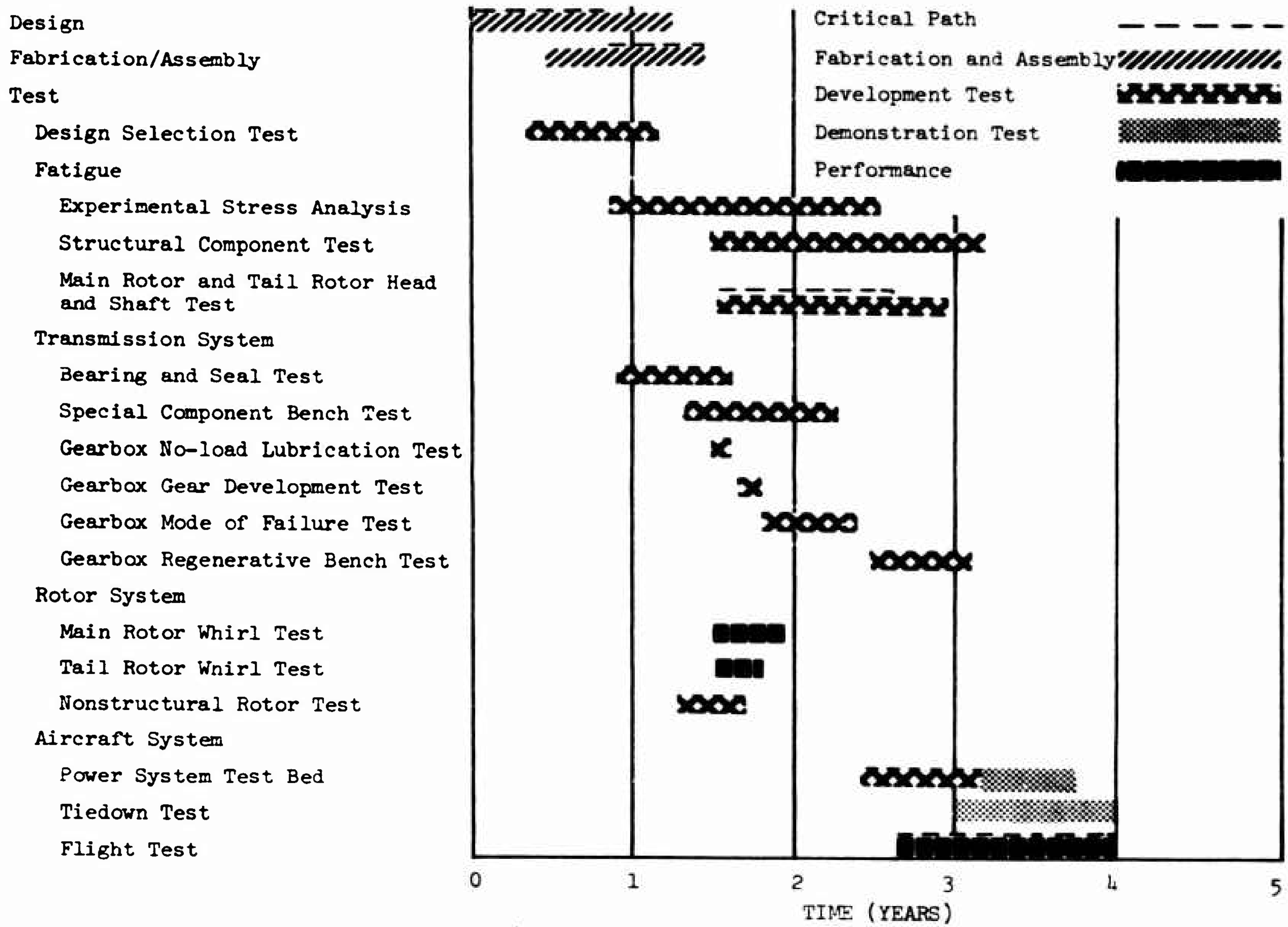


Figure 40. Concurrent Test Schedule.

Preceding page blank

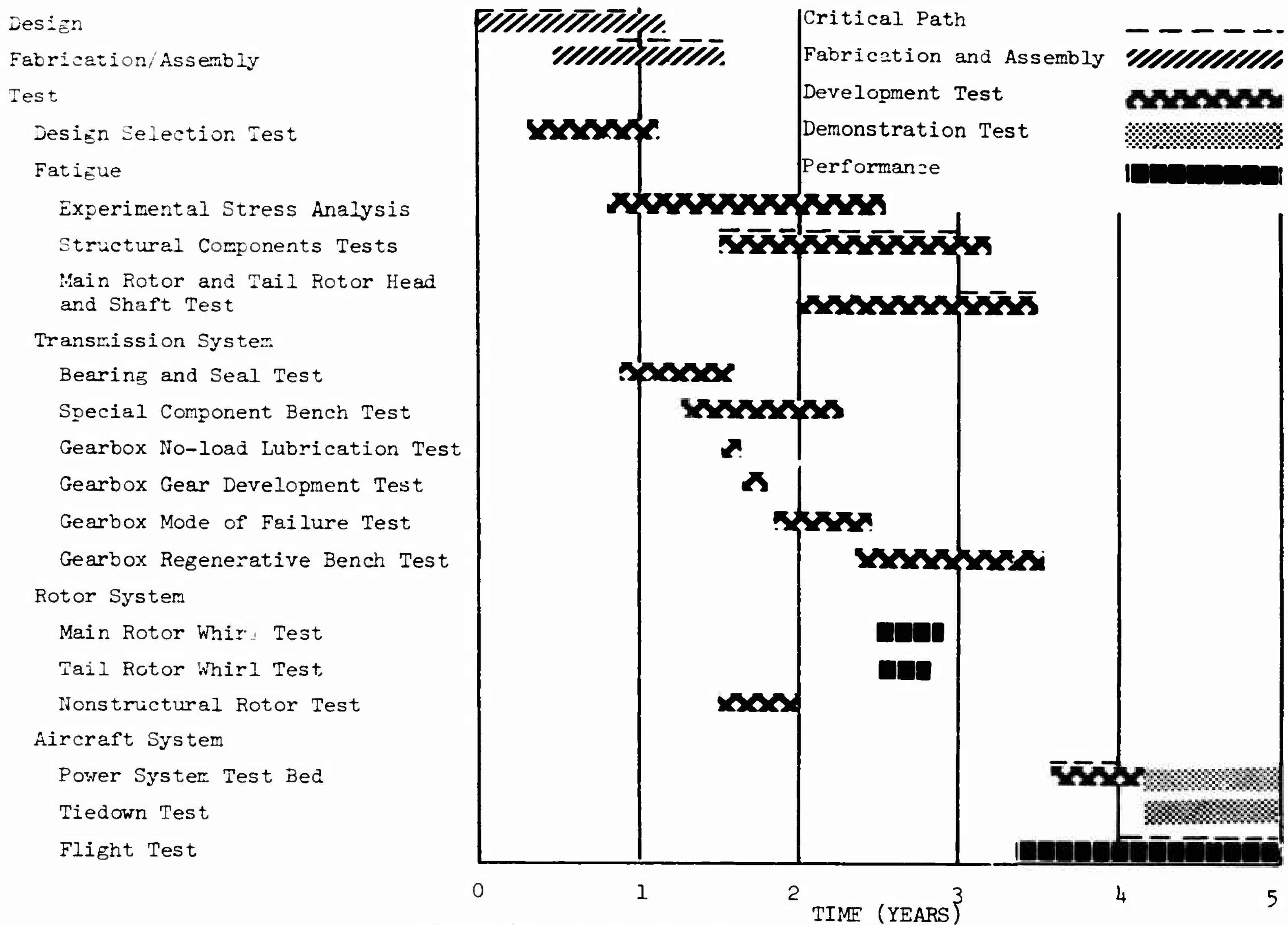
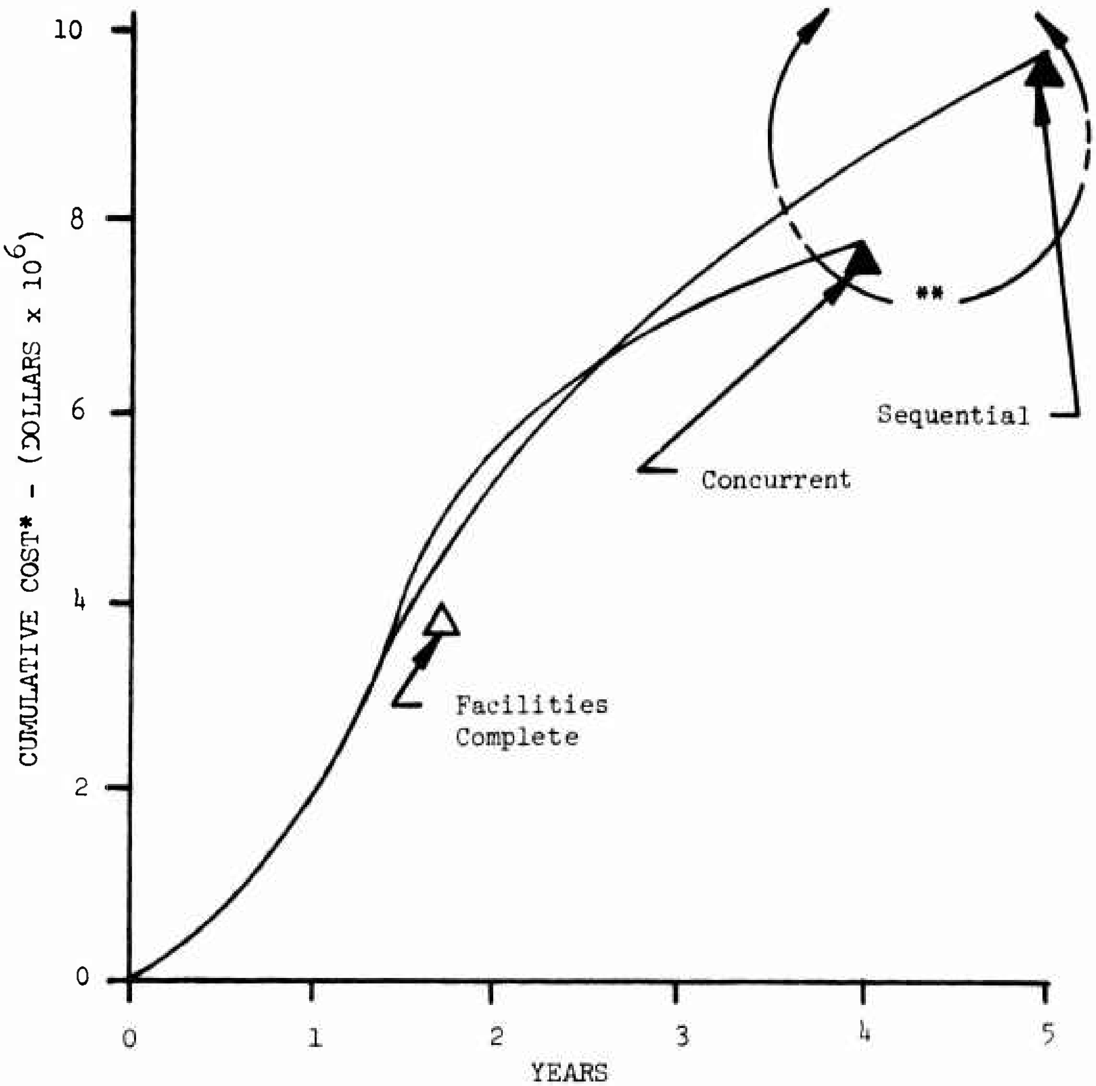


Figure 41. Sequential Test Schedule.



*Includes cost of specimens

**The total cost of the nonconcurrent (sequential) plan is slightly greater than the concurrent plan. The total cost of a test plan could vary by 10 percent.

Includes 120 flight hours of development prior to demonstration.

Figure 42. Cumulative Costs Versus Time at 500-Hour MTBR at 60 Percent Confidence Level.

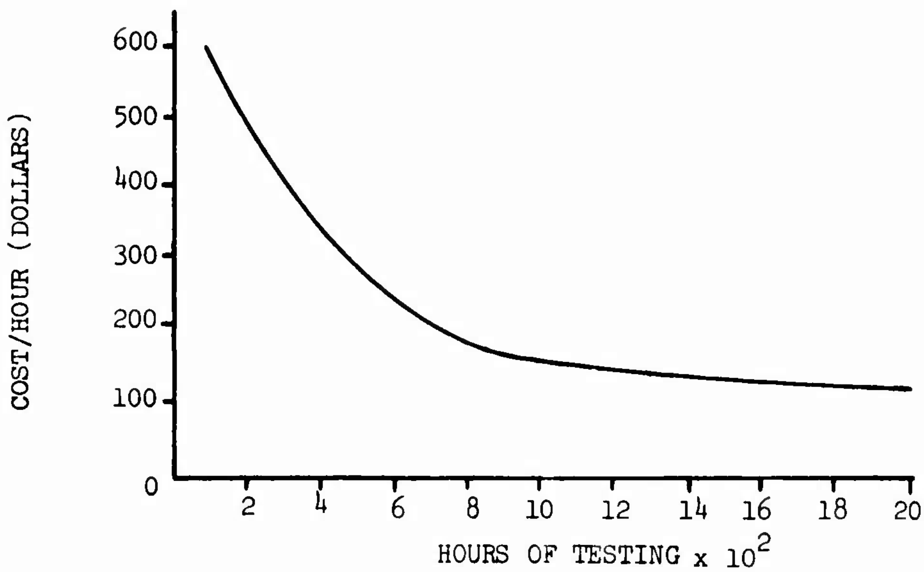


Figure 43. Main Transmission Regenerative Bench Testing Hours Versus Cost.

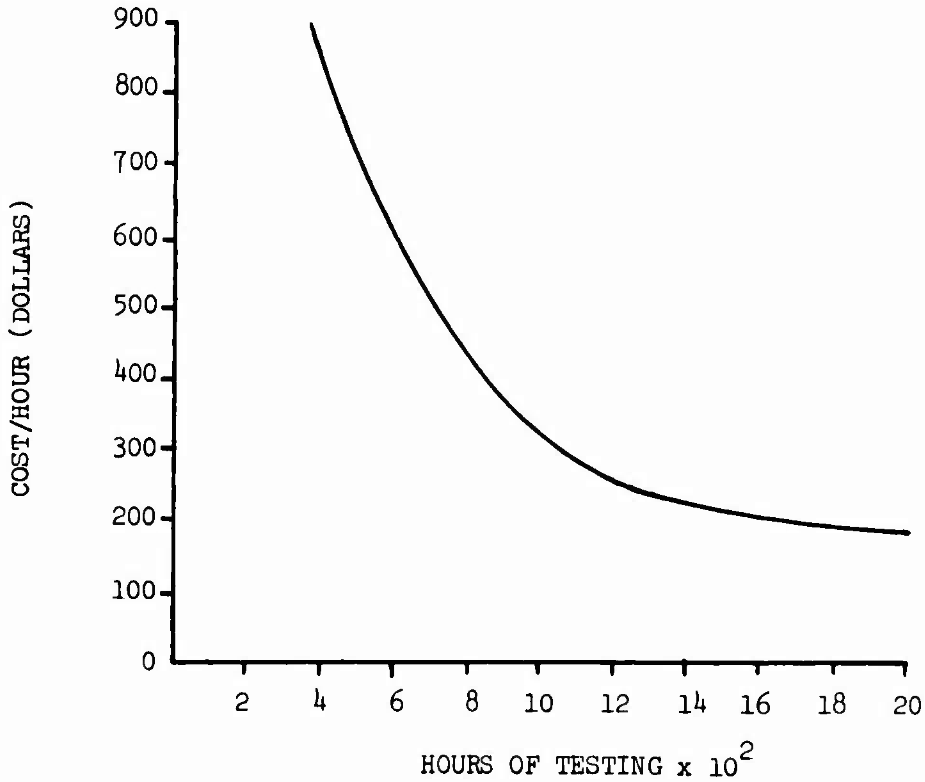


Figure 44. Main Rotor Whirl Testing Hours Versus Cost.

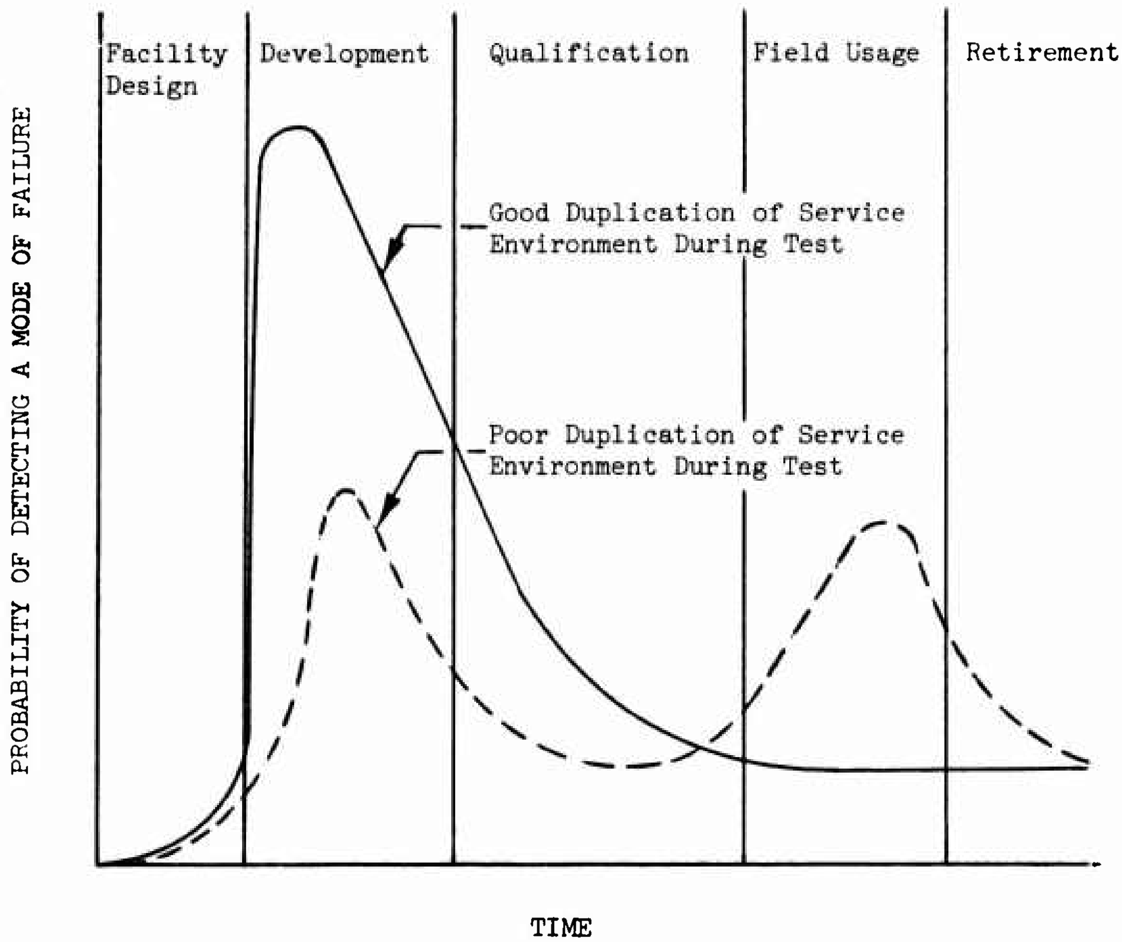


Figure 45. Effect of Environmental Duplication on the Probability of Detecting New Modes of Failure.

function of elapsed time. While the actual numbers are not easily retreived (due to the complexity of many degrees of freedom in this problem), the shape of the curve may be established from several components which are understood. These are design costs, test costs, tooling costs, costs of spares (or salvage), and costs of ECP's.

When nonrecoverable costs of these operations are plotted versus time, as shown in Figure 46, and added, the sum represents the shape of the curve of cost to incorporate a change versus time. When the hypothetical plot of probability of detecting a mode of failure is multiplied by the cost to make the change (i.e., the cost of a change by the probability that a change will be needed), a function proportional to the risk* (in dollars) versus elapsed time is generated. This is shown pictorially in Figure 47.

Note that the risk curve is not an indication of how much money will be spent with time or that a program with poor service environment duplication will definitely cost more money. The curve only gives an indication of how much money the customer should be prepared to spend on an aircraft whose testing has not adequately duplicated service environment. The above argument is also the same for time, since the time required to implement a change on a machine versus elapsed time in a program is of the same general shape as the cost curve. Thus, the risk in terms of downtime is the same as that of risk in dollars. The probability curve shape may also be changed by conducting early prototype or model tests to uncover gross mode of failure, with the corresponding effect as plotted in Figure 48.

This approach obviously has beneficial effects from a risk standpoint. Shortening the time to delivery does not change the curve of probability of discovering a new mode of failure, but it does change the cost of incorporating a change in the system. In short, earlier delivery dates result in higher costs to change earlier in the program. Therefore, the risk (in dollars) increases for earlier delivery dates.

Consider a certain population of machines that were put into service. Barring the possibility of design changes and changes in operating conditions or logistic difficulties, the machines will eventually evidence a downtime inversely proportional to the MTBR and this will be a statistical function, as portrayed in Figure 49.

The MTBF is determined by the operating conditions and basic design, among other factors, and not by test. Testing merely provides an estimate of the value of MTBF for a given design. If the estimate looks bad, then the part must be redesigned. Intuitively then, if a design does not meet its requirements, it would be preferable to know about this as early as possible so that redesign may be undertaken.

Testing of complex systems generally involves large amounts of time and money. Thus, the factors in this trade-off may be considered under one of three major divisions as listed in Table XIII.

*This is not the same as the usual use of the word (i.e., the risk of accepting bad equipment.

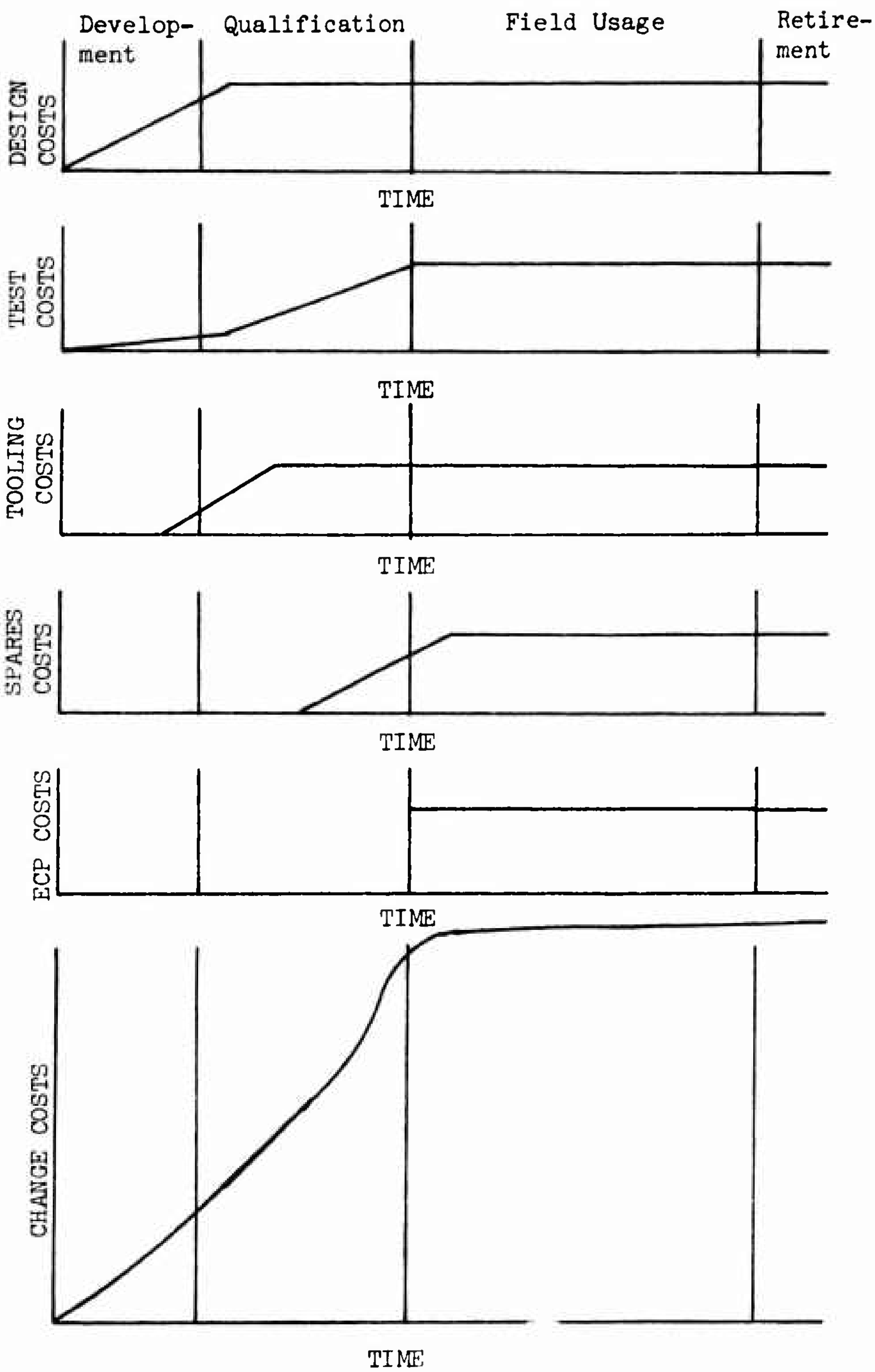


Figure 46. Change Costs as the Sum of Related Costs.

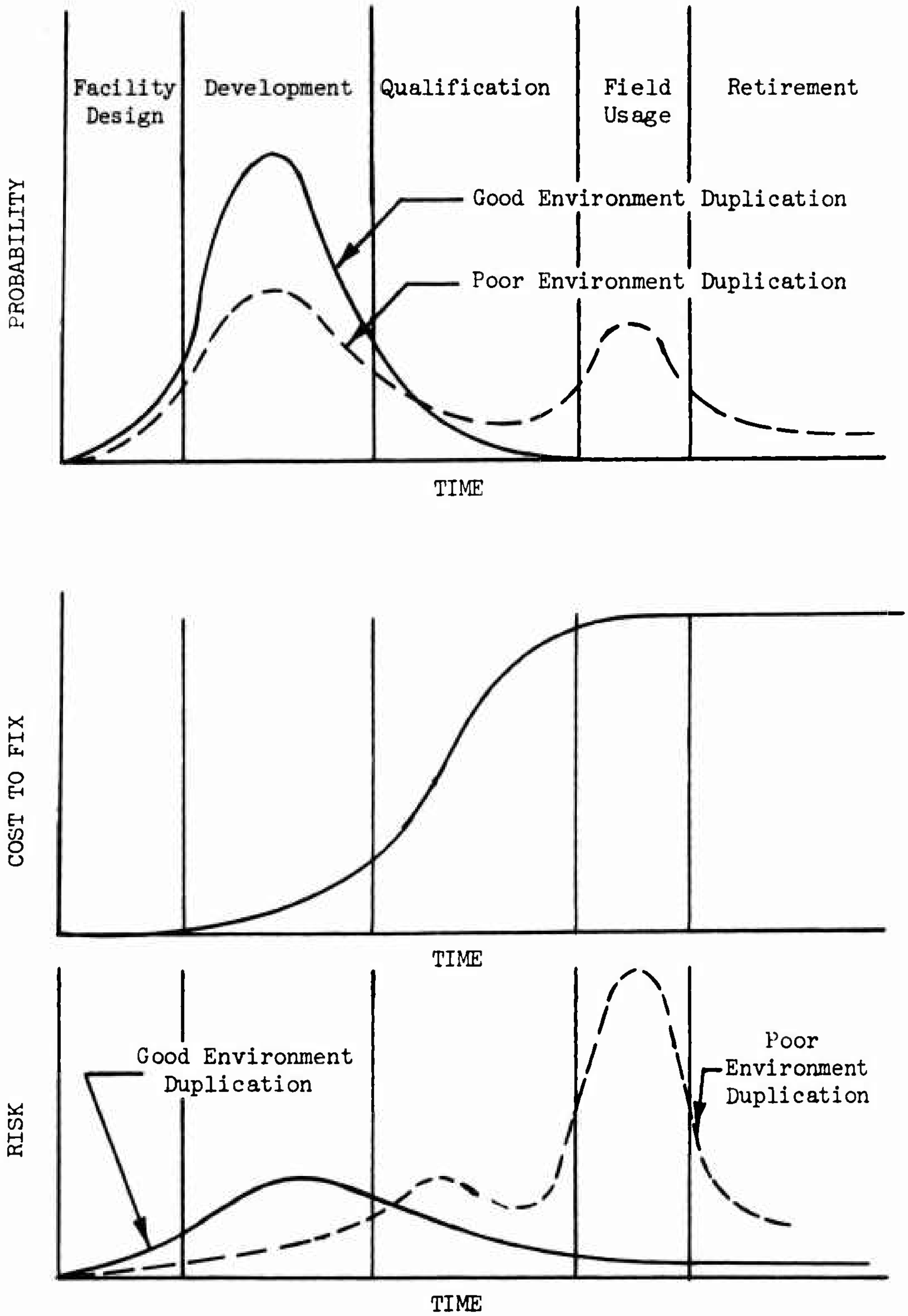


Figure 47. Program Cost Risk as the Product of Cost to Fix, and Probability of Detecting a Mode of Failure.

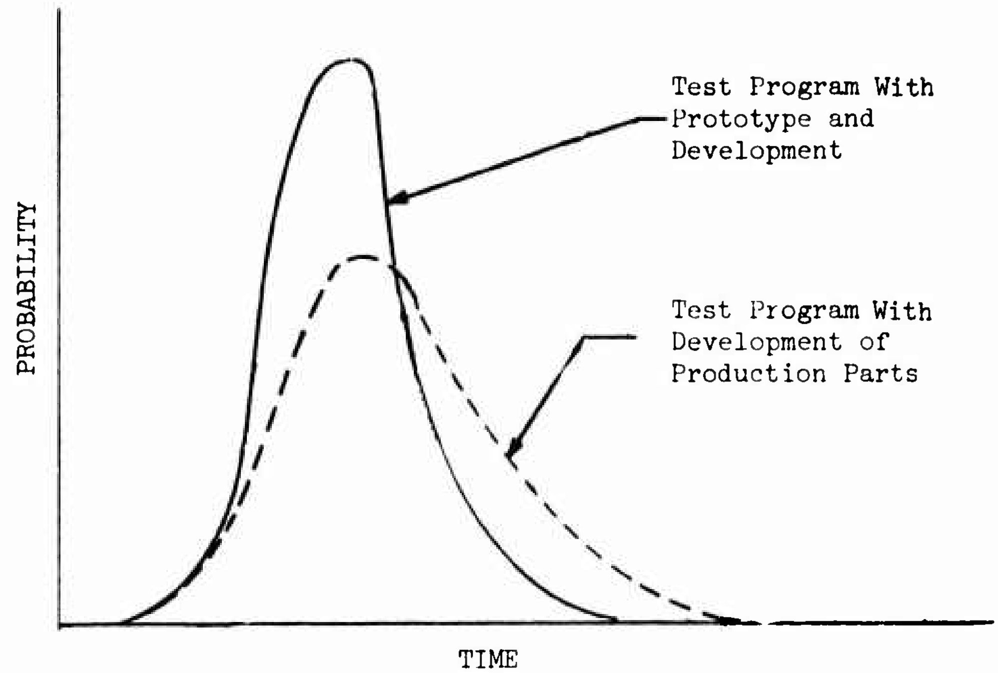


Figure 48. Effect of Prototype Development on Probability of Detecting a Mode of Failure

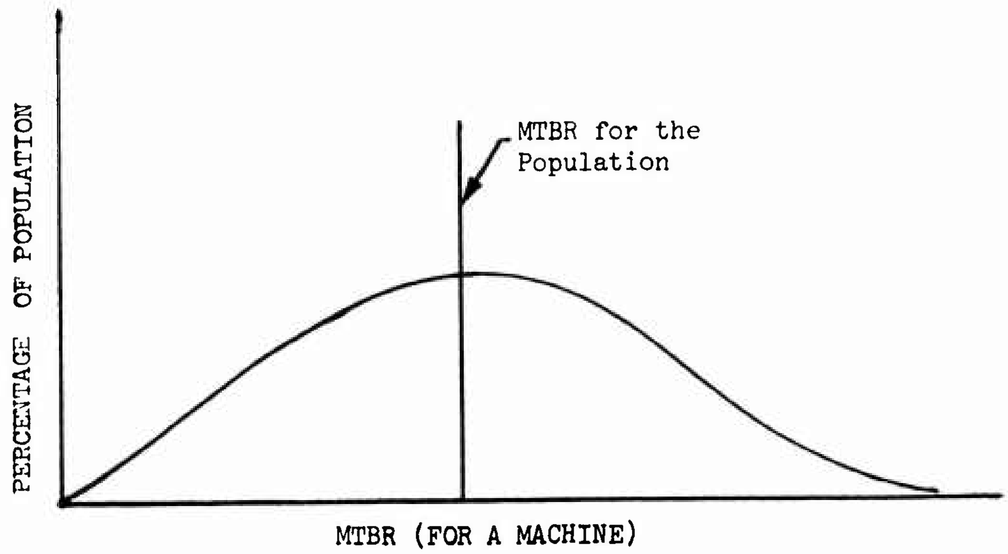


Figure 49. Statistical Nature of the Value of MTBR.

TABLE XIII. TRADE-OFF STUDY FACTORS	
Prime Consideration	Trade-Off Factor
Cost	Cost and number of components needed
Time	Schedule
	Critical path
MTBR	Extent of problem definition and quantification of reliability values
	Reasoning behind acceptance and rejection criteria
	Compatibility with program criteria
	Degree of program flexibility
	Interrelationship of tests and reliability predictions and costs.

The interrelation of three major divisions (and the effect of each factor upon them) is shown in a semigraphical way in Figure 50. As noted in Figure 50, there is some unknown value of MTBF for a given machine which is statistical in nature. This is a function of the design and operating conditions and is independent of either test dollars or time. As such, it constitutes a ceiling.

Consider a hypothetical test plan which adequately duplicates the service environment. This plan will converge on a true estimate of MTBF as time increases, as shown in Figure 51, but if more money is spent ($dollars_2 >$ $dollars_1$) for multiple test or tests which duplicate more interactions with related systems, the estimate will take less calendar time to be adequately defined.

A similar relationship exists (for a given plan) between MTBF and cost, as shown in Figure 52. In addition, time and cost spent in testing to obtain a certain estimate of MTBF are related, as shown in Figure 53.

From Figure 53, several facts are evident:

1. Below a minimum time ($time_1$) the test cannot be conducted regardless of how much money is spent.

2. Below a minimum cost ($dollars_2$) the test cannot be conducted.

3. There is an optimum test time ($time_2$) from a cost standpoint ($dollars_2$) when costs are at a minimum.

4. When calendar time for a test exceeds $time_2$, costs will increase while the data obtained will be less meaningful.

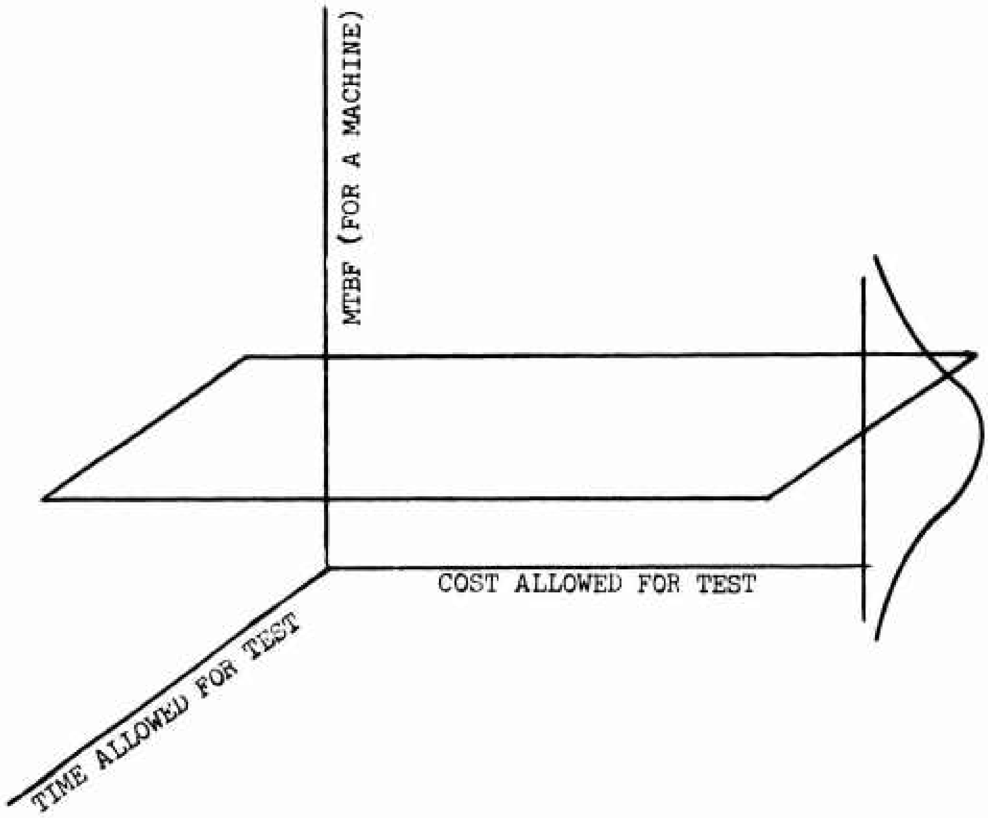


Figure 50. Lack of Interaction of MTBF with Test Program Constraints.

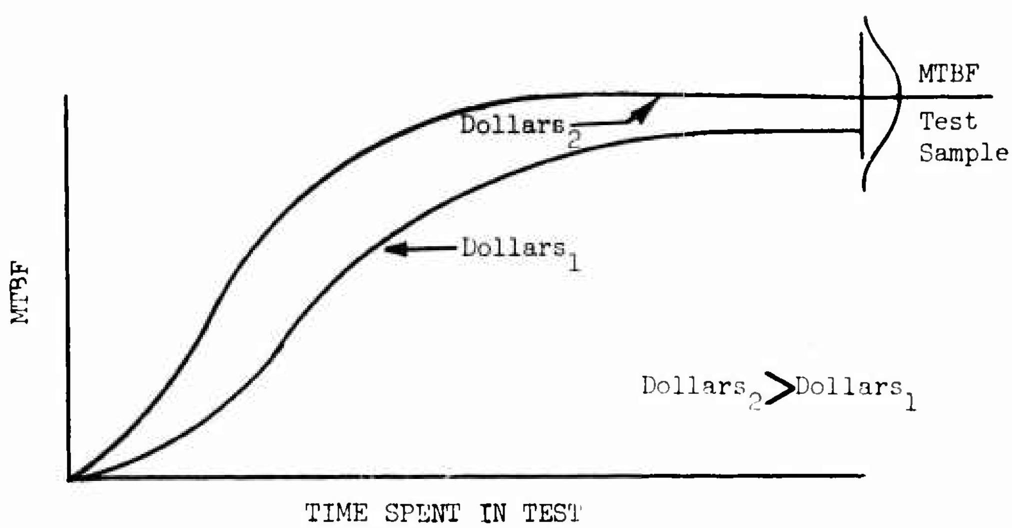


Figure 51. Effect of Cost on the Time Required to Obtain an Estimate of MTBF.

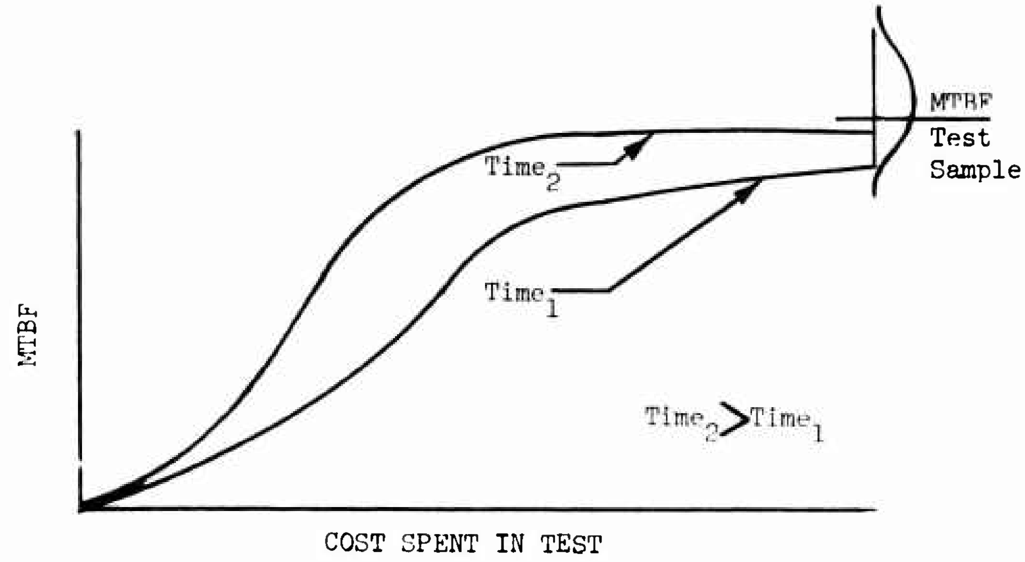


Figure 52. Effect of Time on Cost Required To Obtain an Estimate of MTBF.

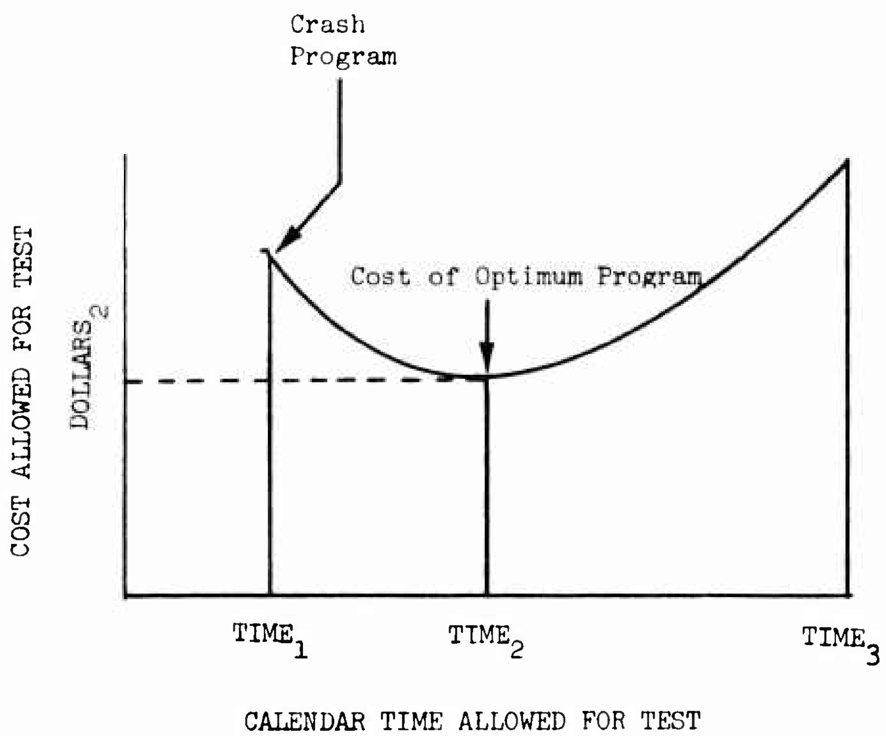


Figure 53. Interrelation of Cost and Time for a Particular Test Plan.

It should be noted to avoid confusion that the test costs represented in Figure 46 are the cumulative cost of test versus time into the test program, whereas in Figure 53 cost is the total allowed dollars (i.e., cost allowed for test) to be expended in testing versus the time which is allowed for conducting the test.

Taken together, Figures 51, 52, and 53 define possible, practical cost-time paths in a given program along which an estimate of the true MTBF of the population may be approached. The two extremes are the crash program, where time is of the essence, and the minimum cost program. The curve shape so depicted may be altered by changing the nature of the test program. Programs are desirable when they approach an estimate of MTBR in less money. This is obtained chiefly by model, prototype, and early mode of failure testing. The cost figures already discussed indicate that locating an optimum within a given program by a 1-year variation in allowable time is not possible due to the tolerances of the estimate. However, differences in test program so affect the curve shape that the greatest saving is obtained by selecting the optimum program first and then optimizing that program.

Figure 54 depicts a hypothetical curve of program cost versus time allowed. Due to the tolerances of the estimates (10 percent), it is not possible to establish the exact nature of these curves. Differences between the selected test plan 1 and the others presented in Appendix I are of such magnitude (4 percent) as to permit the determination of the best of several plans.

EFFECT OF VARYING LEVELS OF RELIABILITY

Demonstration and Development Requirements

Component development and reliability demonstration programs are interrelated with the stringency of the reliability requirement. The higher the reliability requirement and the confidence in obtaining that requirement, the longer and more costly the overall development and demonstration test program becomes. The second trade-off study on the following pages establishes the relationships between the effectivensss (MTBR and confidence level) cost and test duration through examination of the following factors:

1. The approach to be used to demonstrate each of the various reliability requirements.

2. The extent of the development program required to establish the necessary reliability to enter the demonstration program.

3. The cost and duration of the development and demonstration tests.

Demonstration Test Program

The purpose of reliability demonstration tests is to reasonably ascertain the minimum level of reliability (MTBR and confidence of achieving that

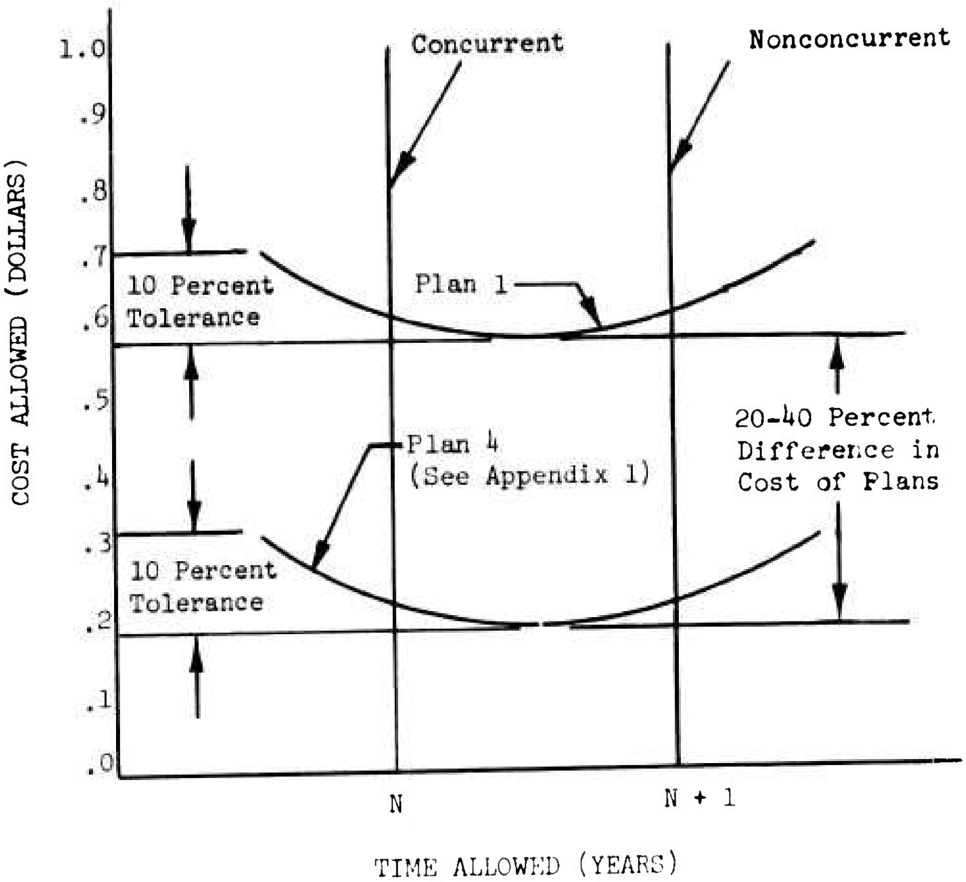


Figure 54. Variation in Cost/Time Relationships Between Plans.

MTBR) that a new helicopter's dynamic components will achieve upon entry into service. The trade-off study of the following pages examines three levels of MTBR, 500, 1000, and 1500 hours, at confidence levels of 30 percent, 60 percent, and 90 percent. The programs of this study have been developed from the basic 500-hour 60-percent confidence level program of Figures 40 and 41.

In any of the following programs several factors impact on the level of MTBR to be demonstrated. Among these factors are component learning curves, component developed MTBF, environmental and loading conditions, and component TBO's.

Component Learning Curves

All dynamic components have a learning curve during which the MTBF increases. The period of time necessary for the component to reach a mature MTBF is dependent upon the amount of development or debugging tests, redesign, and redevelopment effort. In the trade-off study outlined in the following sections, the development testing preceding the demonstration phase provides, in the opinion of the authors, adequate debugging to allow the components to achieve a sufficiently mature MTBF for the MTBR demonstration level desired.

Component Developed MTBF

To minimize the risk of not passing the demonstration test, the helicopter contractor must enter the demonstration with a component whose true MTBF is well above the MTBR to be demonstrated. The margin of true MTBF to MTBR to be demonstrated varies with the risk that the helicopter contractor (and ultimately the customer) is willing to assume and the duration of the demonstration program. The greater the margin desired, the greater the development requirement for the component.

Environment and Loading

Test environment and loading must reasonably agree with those to be experienced in service, or a relationship between test and service conditions must be established if the comparison between demonstrated MTBR and projection of service MTBR is to be meaningful. Also it is recognized that accelerated testing could and should be considered as a means of reducing cost and duration of the test program. This topic is discussed later. However, for the purpose of this trade-off, it is taken that the demonstration test environment and loads are the same as in service and no accelerated loading is considered since it would have relatively equal effect upon the various test programs being considered.

Component TBO

The time-between-overhaul, TBO, as established by the user has a major effect on actual MTBR. Actually the component MTBR is a combination

of the component's TBO and MTBF. Assuming a mature population (all components have passed through several overhaul intervals) and a constant failure rate between overhauls (which has been proven true in most cases), Figure 55, obtained from Equation (1), provides this relationship.

$$MTBR = MTBF\left(1 - e^{-\frac{TBO}{MTBF}}\right) \qquad (1)$$

As may be seen, imposing a TBO drastically increases the MTBF required for a particular MTBR. For example, for on-condition overhauls, a 1000-hour MTBF = a 1000-hour MTBR, but if a 2000-hour TBO is imposed a 1000-hour MTBR requires a 1250-hour MTBF. The 2000-hour TBO assumed is considered to be the average state-of-the-art level and is used through the following trade-offs. Examination of Equation (1) indicates that a high TBO, well above the MTBR to be demonstrated, is required. Appendix II discusses the establishment of high TBO's. In addition, it introduces an analytical tool known as the Failure Rate Analysis Program (FRAP) which allows the establishment of economically sound high TBO's. Further, it demonstrates the use of FRAP in the analysis of four major H-3 dynamic components.

With the foregoing considerations taken into account, Figure 56 was developed. It shows the relationship between the duration of demonstration testing and the number of permissible failures of the component in question for each level of component reliability and confidence. The demonstration test hours shown in Figure 56 are the total accumulated hours on all component samples tested during reliability demonstration tests. From this figure and Table XII outlining average test costs, the program manager can plan a demonstration test program.

Development Test Program

The purpose of the development program is to achieve a level of component MTBF which will allow a maximum confidence of passing the demonstration test. As was discussed previously, the required margin between component true MTBF and the MTBF associated with the MTBR to be demonstrated varies with demonstration duration. For any given level of reliability to be demonstrated, the greater the duration of demonstration testing, the lower the required or developed MTBF, hence, the less the development test requirements. The following data, presented in graphical form in Figures 57 through 61 and used in conjunction with Figure 56, substantiate this fact.

The experience with the H-3 helicopter of the 15,000-pound gross weight range is discussed earlier in this report. The ability to "grow" the MTBF through development testing is presented in the section "EFFECTIVENESS OF TESTING" with the aid of Figure 36.

The main gearbox and the main rotor head curves of Figure 36 provide

the basic data from which working curves representative of helicopter dynamic components can be constructed. These curves, in turn, can be used as a tool in test program cost/duration studies. Figure 57 was developed from the data of Figure 36. This data establishes the shape of the curve of development test hours versus required component mean time between failure in hours as presented in Figure 60. Guidelines used to accomplish this relationship are described below. Observation of the main gearbox and the main rotor head test curves in Figure 36 shows that they are basically the same shape. Within the accuracy needed for preliminary program planning, the lower curve was selected to estimate overall costs of dynamic component development tests. The curve selected eliminates unnecessary repetitive detail in estimating costs and if anything is more realistic, since in the past inadequate estimates of test costs have been made.

The slopes of the curves in Figure 36 provide failure rates, and in turn their reciprocal values yield the anticipated mean time between failures of dynamic components. Thus, at increments of development testing applicable to each dynamic component an instananeous MTBF can be established. Each of these MTBF's is calculated in terms of percentage of increase relative to the initial instananeous MTBF at zero test hours as a base. The plot of percentage of increase in MTBF versus test duration is presented as Figure 57.

As may be seen, the first 3000 hours of development testing produces only small increases in MTBF over and above the off-the-board component MTBF but is required to debug the equipment and make it operational. From 3000 hours on the percentage of increase in dynamic component MTBF is, from past test experience, nearly linear with test duration.

If it were desired, a separate growth curve for each of the various types of testing can be developed. These curves are shown in Figure 58. They reflect the relative operating hours per failure as stated in Table II. The primary reason for component tests requiring fewer hours than system tests is the capability of the component test rig to accelerate loads and produce failures in shorter periods of time.

Using the basic linear growth shape developed above and shown in Figure 57, a growth curve for any given component can be determined if the off-the-board component MTBF is known. For the purpose of this study, the values which follow are taken as currently achievable off-the-board MTBF. As noted before, with new or redesigned components approximately 3000 hours of development testing are required to debug the component before it could become operational. Main gearbox, 1500 hours MTBF: main rotor head and tail rotor head, 1000 hours MTBF; and intermediate and tail gearboxes, 5000 hours MTBF. These values have been demonstrated on current designs with previous test and service experience. From these initial values and the linear behavior of Figure 57, the curves of Figure 59 can be established. Then taking these component curves and weighting them by test cost, a composite curve which can be used for estimating the necessary development test hours for major helicopter dynamic components to obtain any desired component development MTBF can be established. This relationship is shown in Figure 60. In generating this curve, a reasonable extrapolation was made beyond the currently

available data of Figure 36. It reflects a life acceleration factor of 2.

In the upper region of the curve it is felt that the effectiveness begins to diminish with increased testing. This is true since the development testing discloses the modes of failure and redesigns, in turn, are made for correction of these failures; more and more testing is required to not only disclose newer modes of failure, but also to establish that the fixes are effective.

Figure 61, drawn for 10 percent producers risk, relates test duration and expected quantity of failure to a true level of MTBF. The curve may be entered with the demonstration test parameters determined from Figure 56. Figure 61 also relates the true level of MTBF (MTBF out of development) to the required development test hours, using the relations shown in Figure 60.

Cost and Duration of Program

Having selected a demonstration program to prove the required level of reliability and a development program to achieve a sufficiently high level of reliability to minimize risk, cost and test duration can now be determined.

The types of tests to be conducted (such as regenerative bench tests, propulsion system test bed, tiedown aircraft, rotor head and shaft test, rotor head whirl stand) and their respective cost are presented previously. Considering time and facility limitations, optimum quantity of test specimens and concurrent versus sequential testing considerations can be studied.

The following limitations were assumed for this trade-off:

1. Total program time frame was 5 years.

2. The number of required development test hours as determined from Figure 60.

3. The number of development test hours attainable on test facilities is as presented in Table XII.

4. The number of required demonstration hours is as determined from Figure 56.

5. The number of demonstration test hours attainable on a tiedown aircraft facility is 100, as presented in Table XII.

Within the above limitations, each of the nine levels of reliability was studied (three MTBR's each at three levels of confidence). For each level, demonstration program was selected; an appropriate development program was selected; test facility and test specimen requirements were determined; and cost and calendar time was determined.

The findings are presented graphically in Figures 62, 63, and 64. These cost versus time curves do not include flight test, since it is proposed

that the development and demonstration will be conducted during the ground test phase. In these plans, flight testing will be used primarily for performance work and only as a supplement to development effort.

To determine the total cost of the programs, approximately $1,500,000 of flight testing can be added to the curves of Figures 62, 63, and 64.

Effects of Acceleration

As discussed previously, it was assumed for the purpose of the trade-off study that the demonstration test loads were the same as in service. However, it is recognized that major savings can result in the cost and duration of development and demonstration testing with the introduction of load/life acceleration factors. Accelerated testing can uncover more failure modes and establish design changes and demonstration power/environmental influenced reliability factors in considerably less time. If a straight one-to-one load/environment spectrum is employed, the development and/or demonstration time is greatly increased over the accelerated approach.

However, the adjusted calculations used to convert actual to equivalent test times must be based upon whatever data bank is available from similar components and engineering judgment. An additional risk is included in accelerated testing in that this data bank must accurately reflect the new design practices.

The load acceleration factors used in the various tests should maintain the resulting deflections and stresses within practical limits and not cause unrealistic modes of failures in the components. For normal endurance test programs, the power should be no more than 110 to 120 percent of the maximum torque rating of the gearbox. Speeds should be limited to 110 percent of maximum values, and thrust loading to 120 percent of the maximum anticipated loading. For high torque development tests (mode of failure), the acceleration factors can be increased up to 140 percent for both thrust and torque and 110 percent for speed.

For example, if a main gearbox were to be demonstrated using a load acceleration factor greater than one, more gear and bearing failures would be expected than if one-to-one spectrum loading were used. But other failures (such as seal leakages) may be unrelated to the accelerated loads. Failure rates for this type of component can be projected based on past gearbox (or rotor head) service history, and a total anticipated failure rate for accelerated testing can then be established from these and the accelerated test results by analysis.

Considering these facts, it is recognized that accelerated testing is most effective during the initial phases of development testing. In this stage of the test program, the major goal is the uncovering of the weak links and major failure modes (principally those associated with structural reliability). The relationship between accelerated and unaccelerated development test hours is given in the curves of Figure 65. The curves of Figure 65 are based on the accepted life/load relationship for various dynamic components. The acceleration factors, for the life/load relationship

for bearings are as established by the bearing industry; for gears, as established in the American Gear Manufacturers Association Standard Procedure, 411.02 for Aircraft Engine, Power Take-off Spur, and Helical Gears, and in the Gleason Bevel and Hypoid Gear Design Manual; and for other structural components, as presented in the design procedures manuals of the aircraft industry. These relationships demonstrate that raising the mean (or prorated) load used in development testing should accelerate the time-to-failure of the components in the ratio shown. For example, bearings operated at mean (or prorated) loads 50 percent higher than those experienced in service should have their life reduced by a factor of 4.

Accelerated or overload testing should be employed in the initial development tests of a major program to reduce development test time. The "RECOMMENDED TEST PLAN" includes an accelerated test approach in both the development and demonstration test phases.

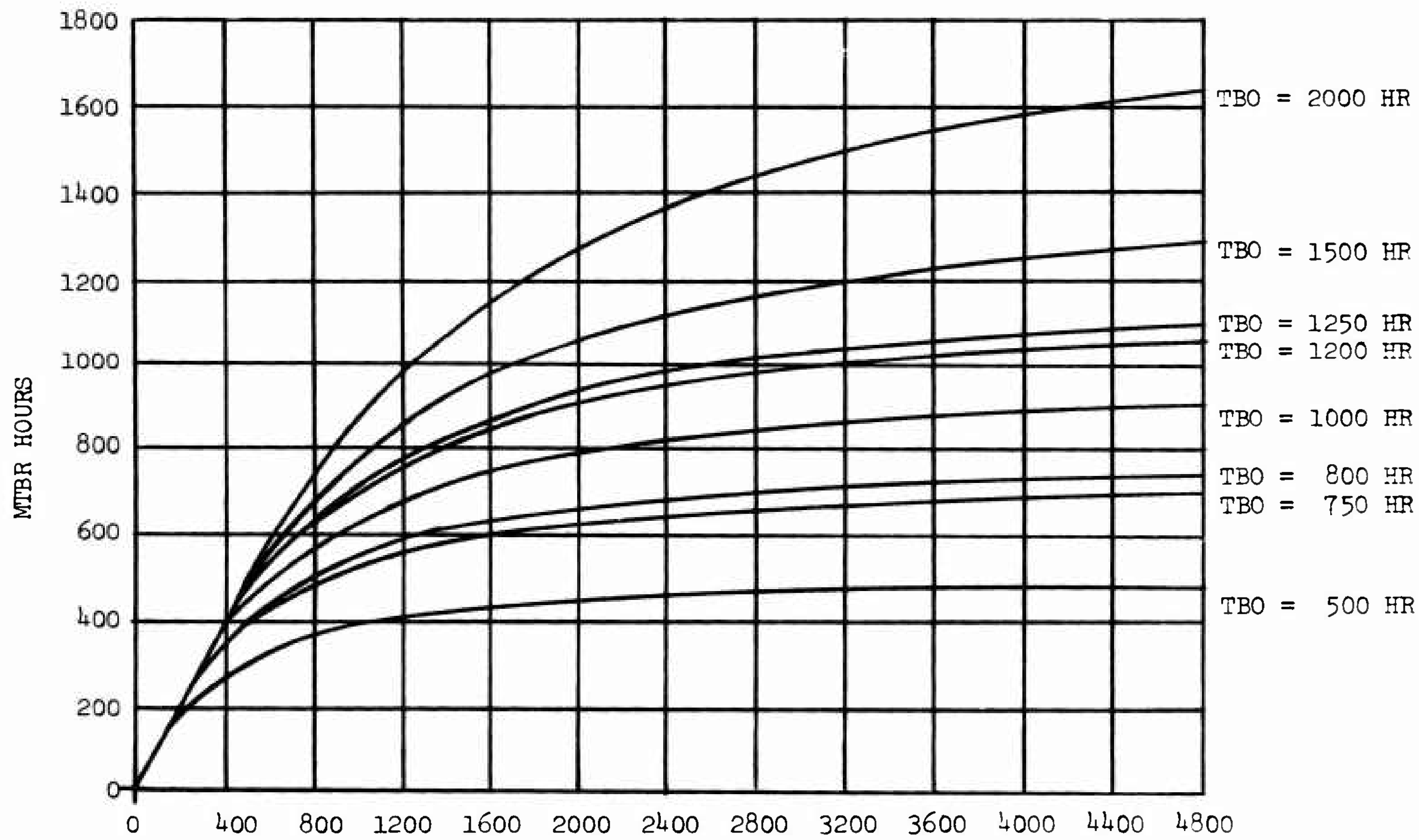


Figure 55. MTBR Versus MTBF for Constant TBO's.

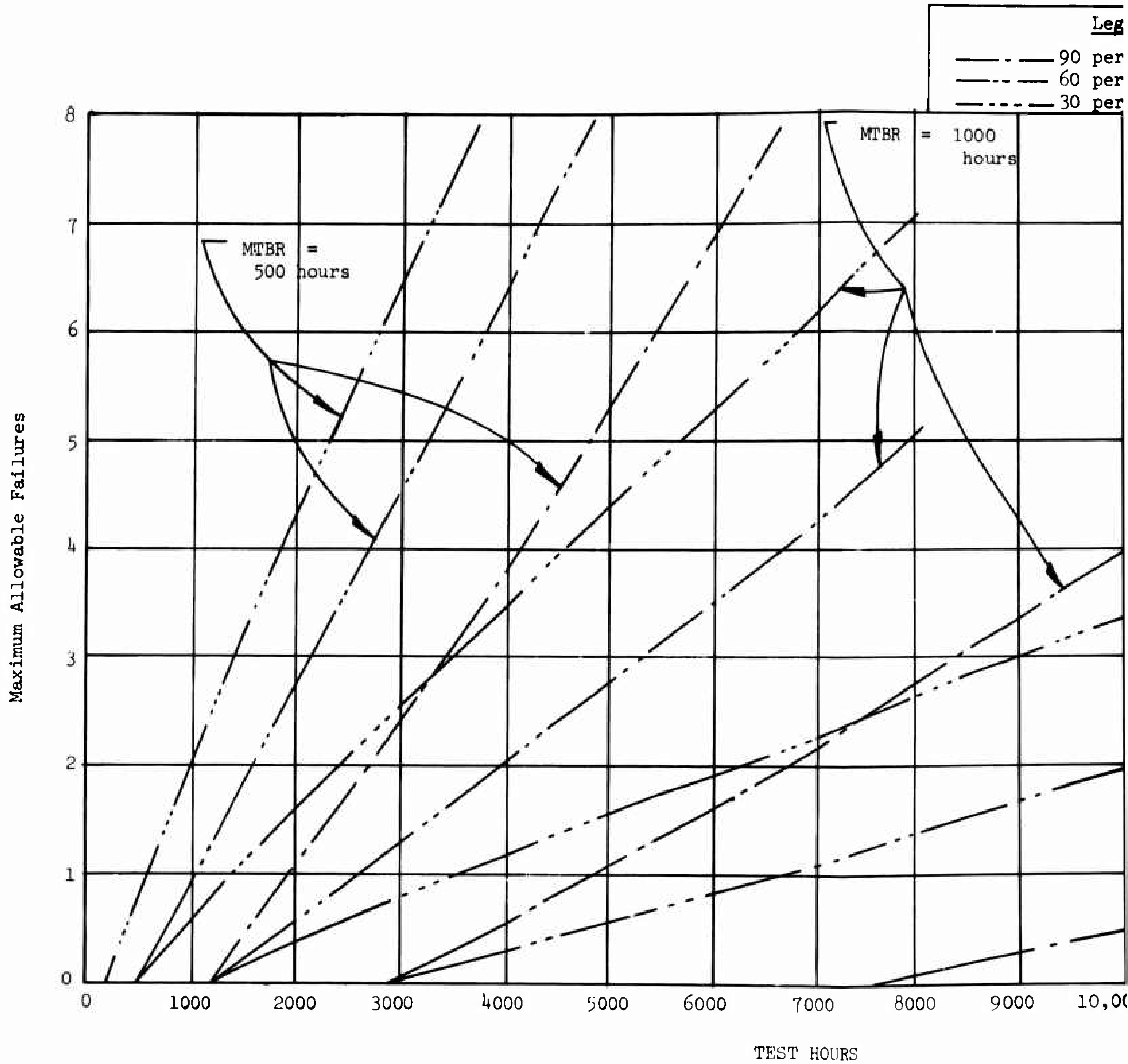
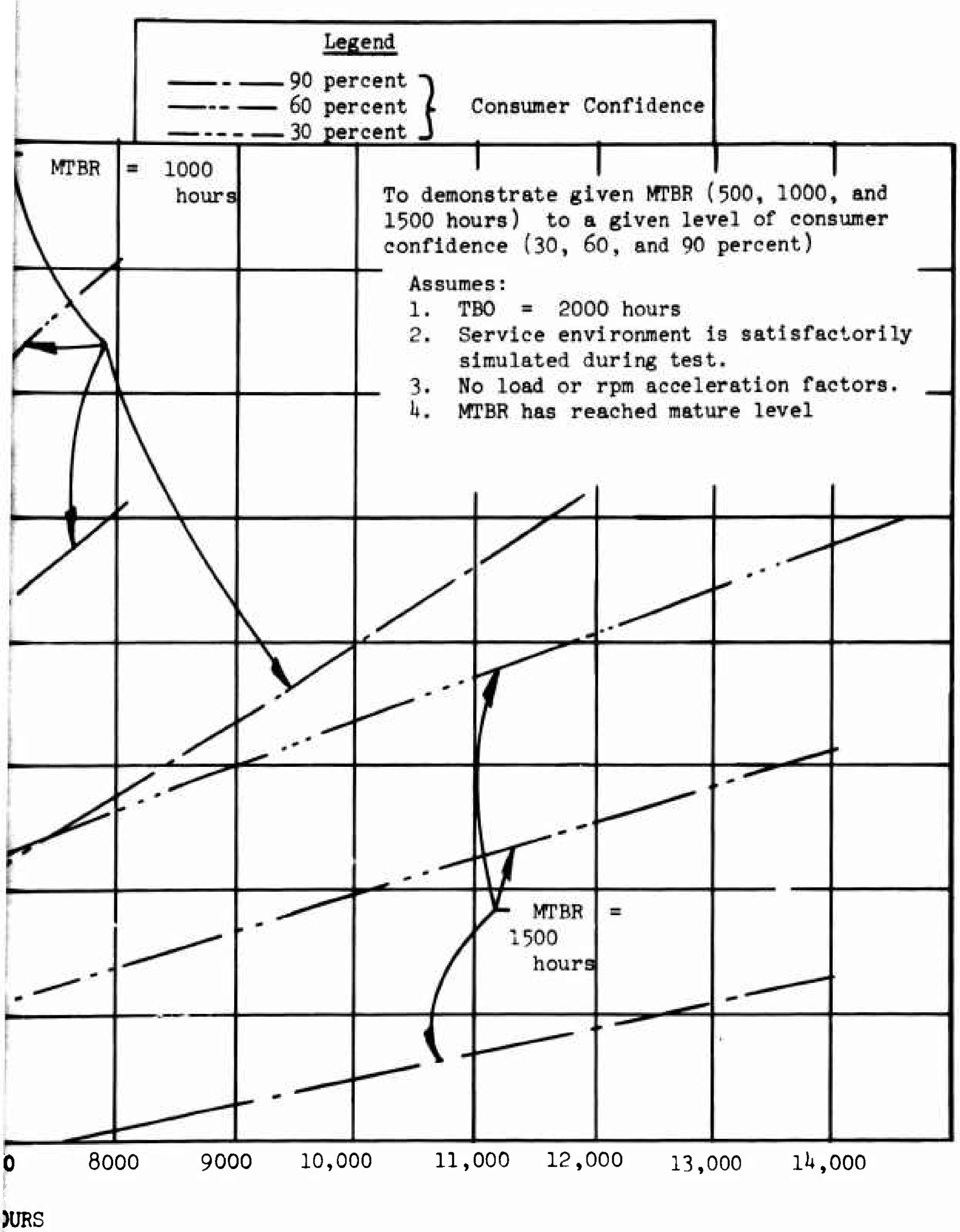


Figure 56. Test Hours Versus Maximum Allowable Failures.

Preceding page blank


Legend
90 percent
60 percent
30 percent
Consumer Confidence
MTBR = 1000 hours
To demonstrate given MTBR (500, 1000, and 1500 hours) to a given level of consumer confidence (30, 60, and 90 percent)
Assumes:
1. TBO = 2000 hours
2. Service environment is satisfactorily simulated during test.
3. No load or rpm acceleration factors.
4. MTBR has reached mature level
MTBR = 1500 hours
0
8000
9000
10,000
11,000
12,000
13,000
14,000
URS

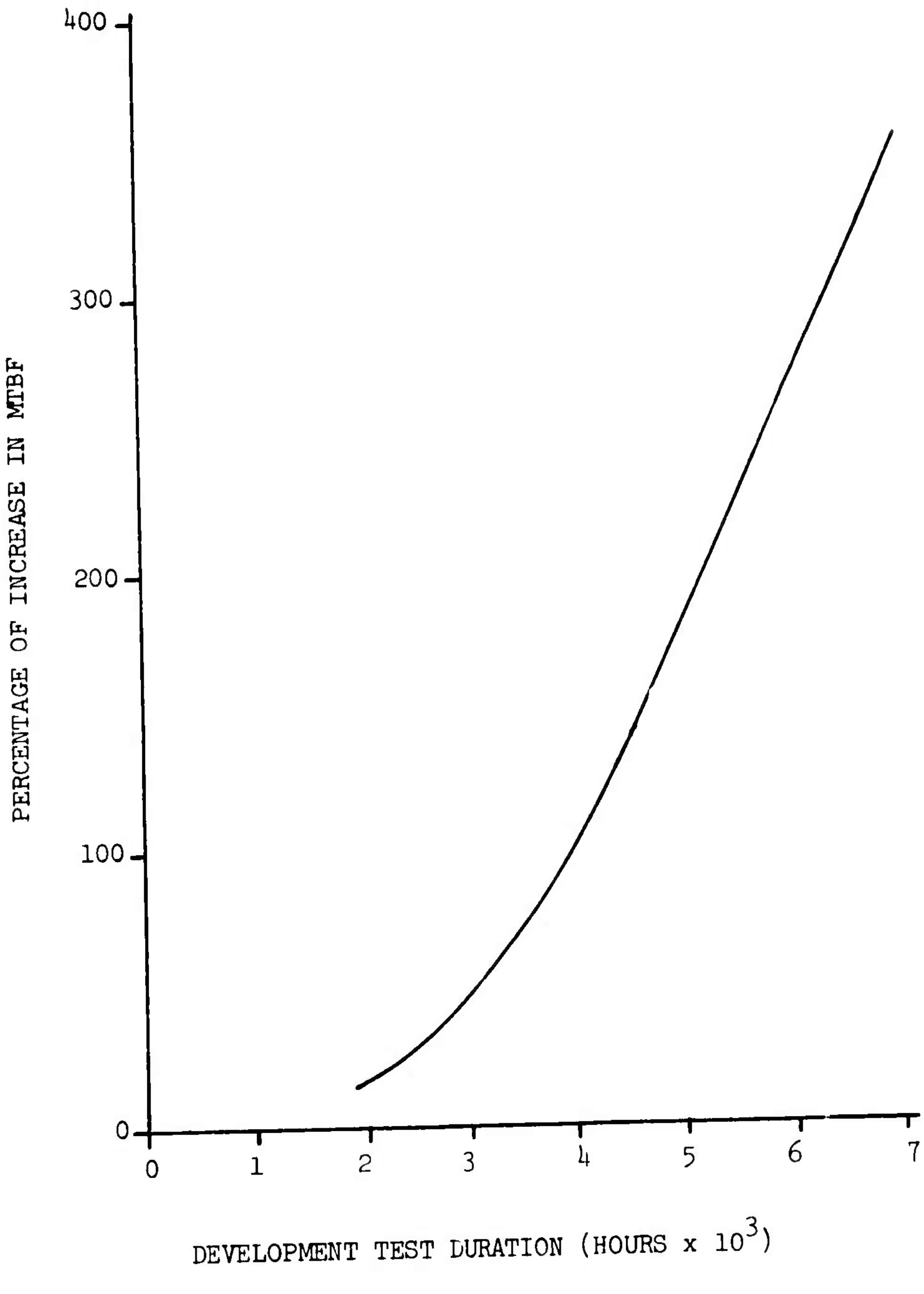


Figure 57. Plot of Percentage of Increase in MTBF
Versus Development Test Duration.

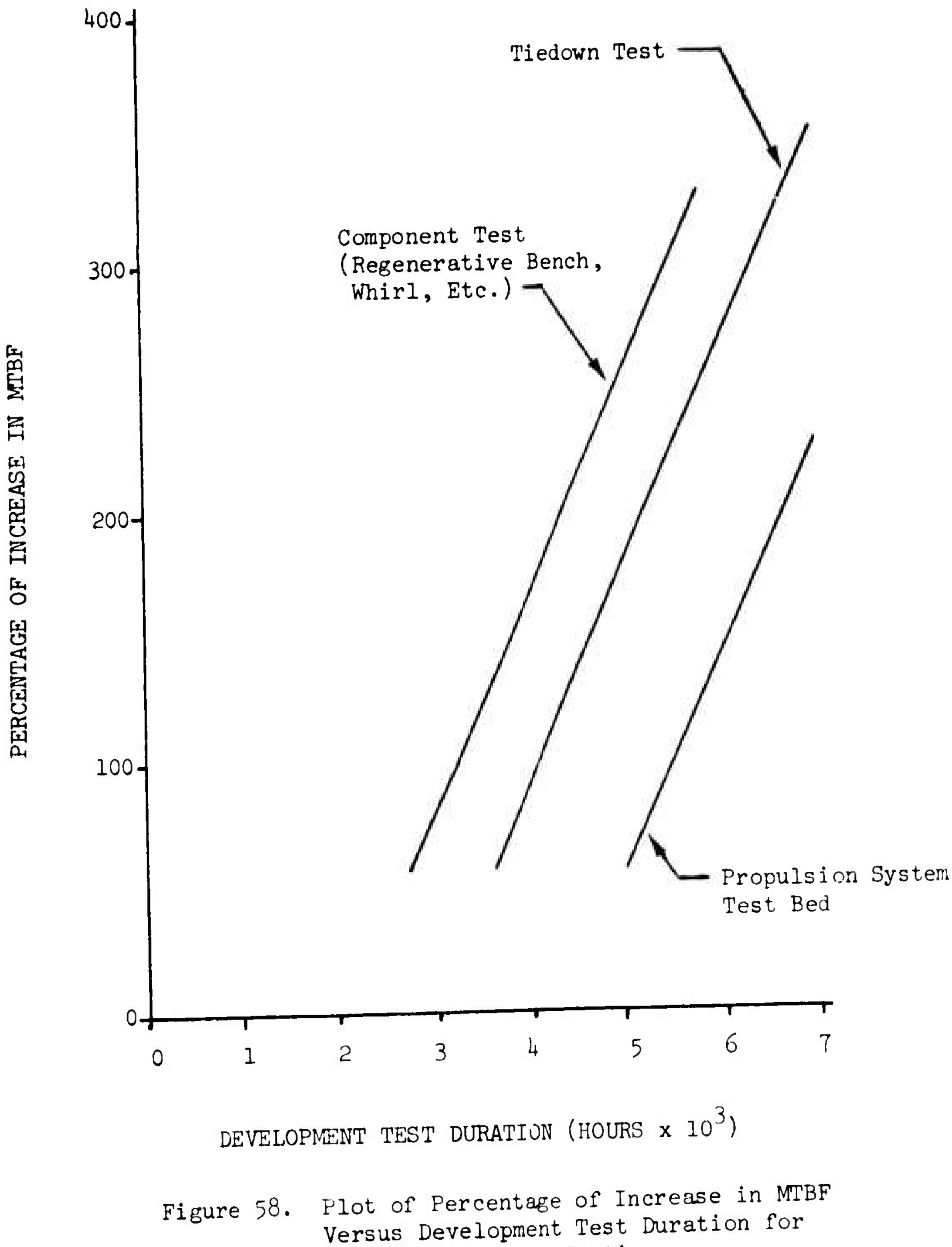


Figure 58. Plot of Percentage of Increase in MTBF Versus Development Test Duration for Various Levels of Testing.

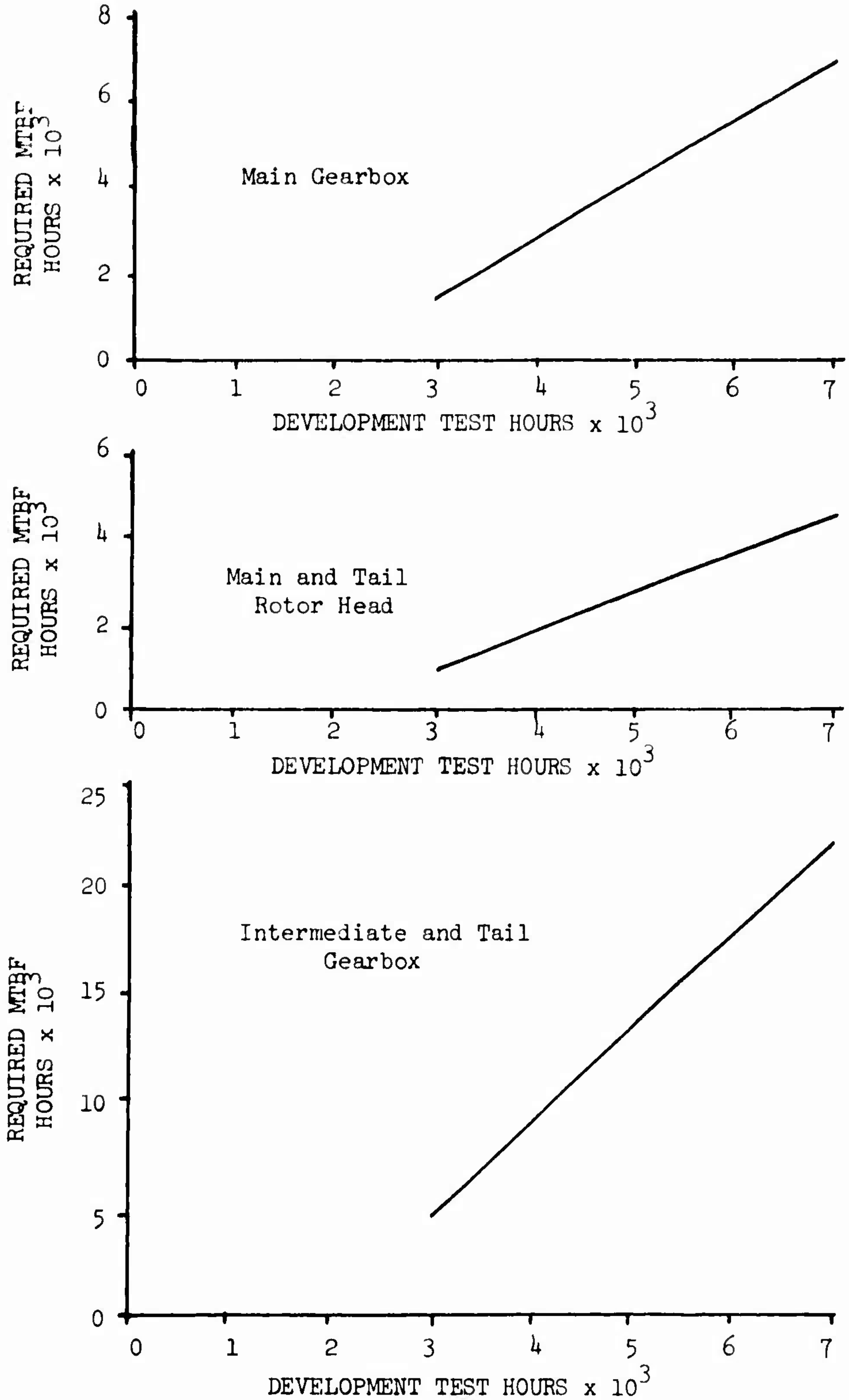


Figure 59. Various Components MTBF Versus Development Hours.

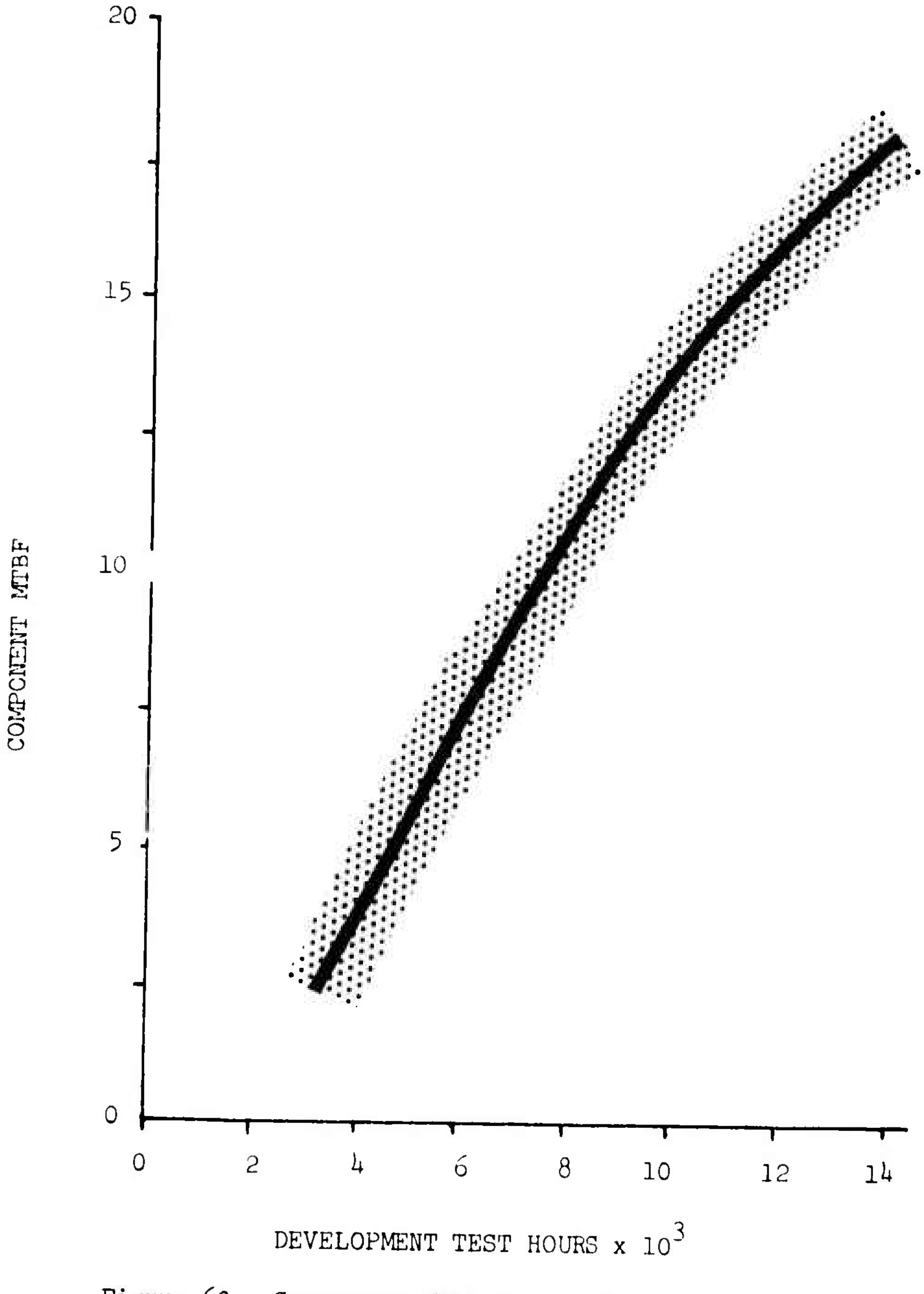


Figure 60. Component MTBF Versus Development Hours.

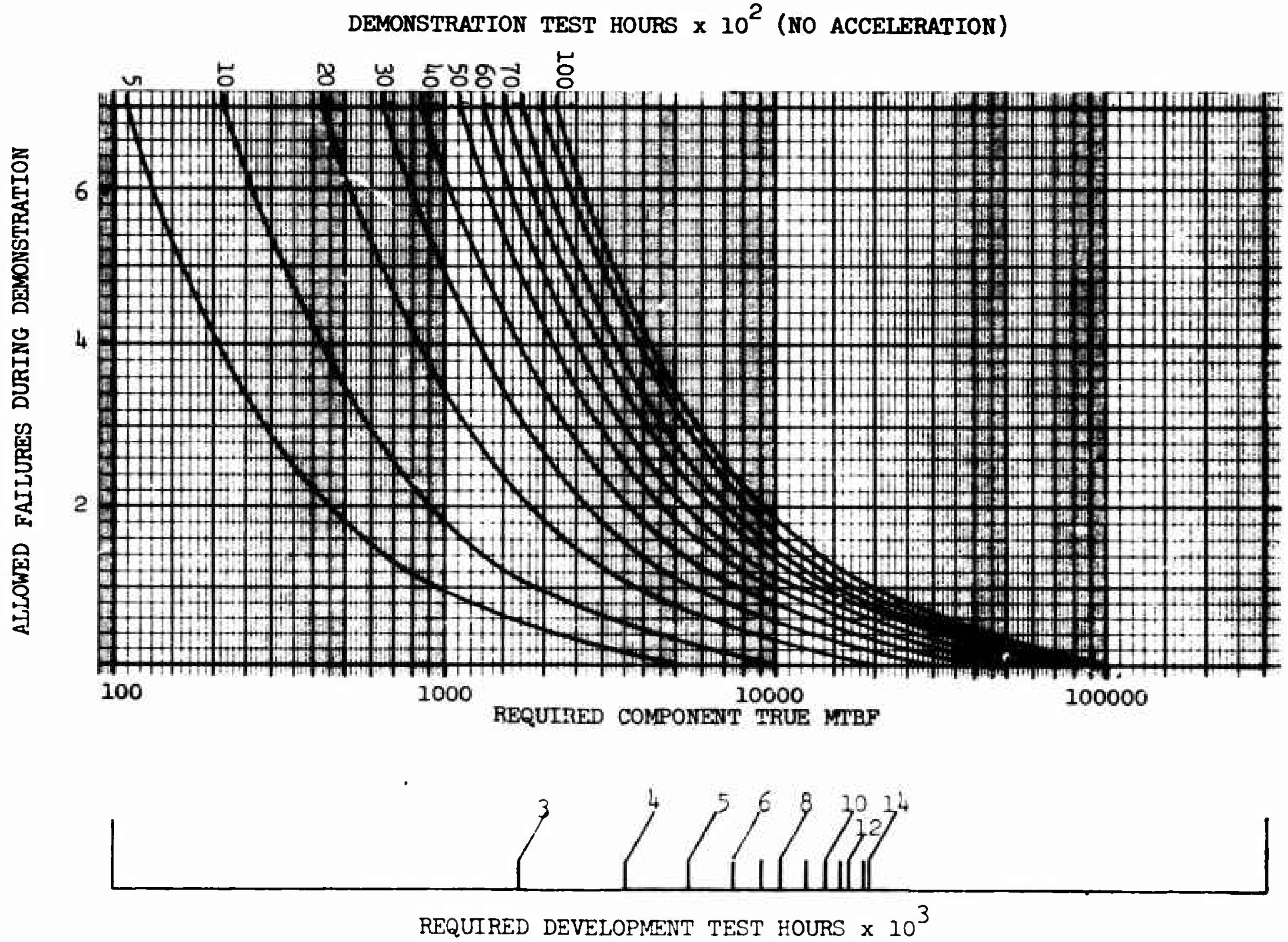
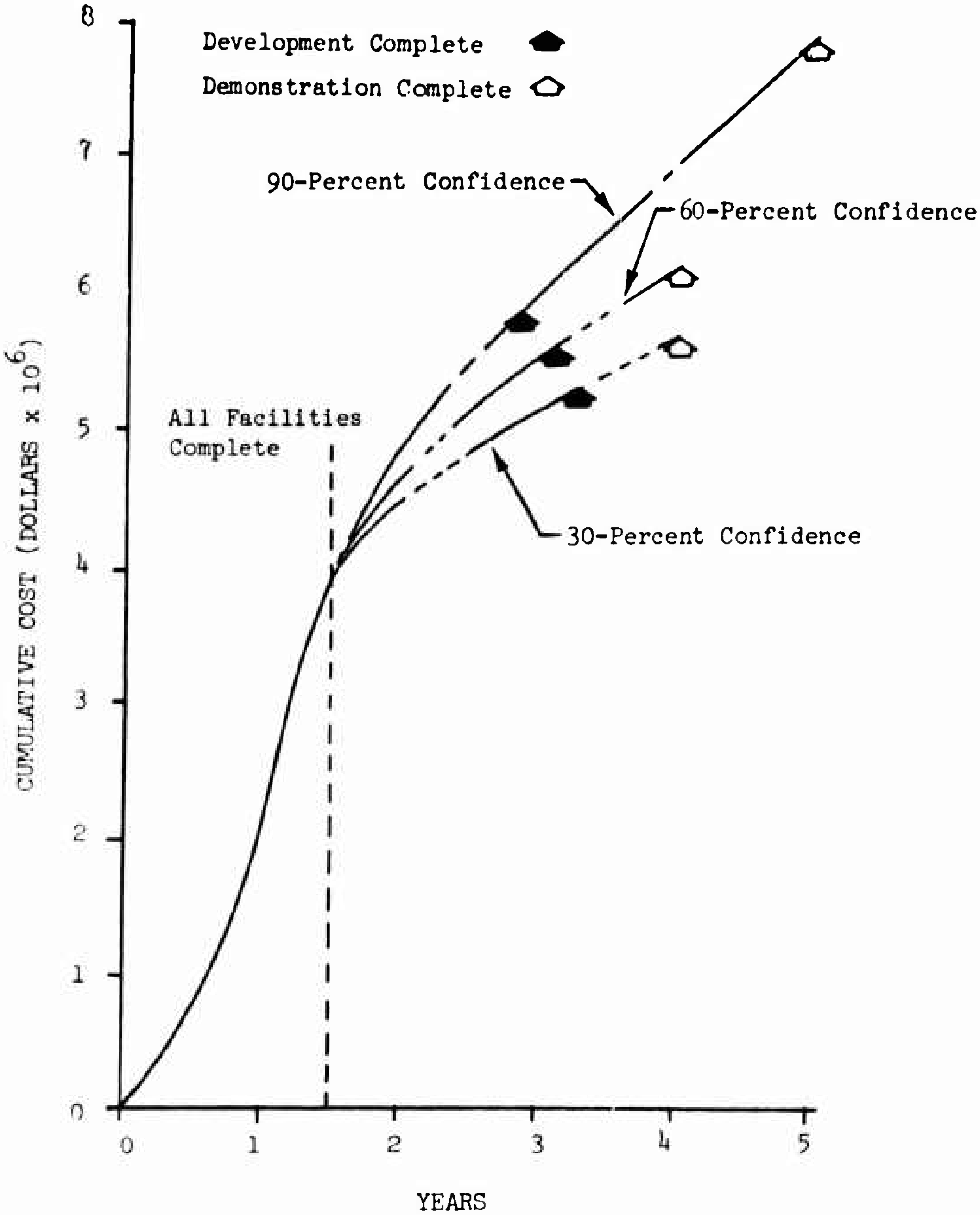
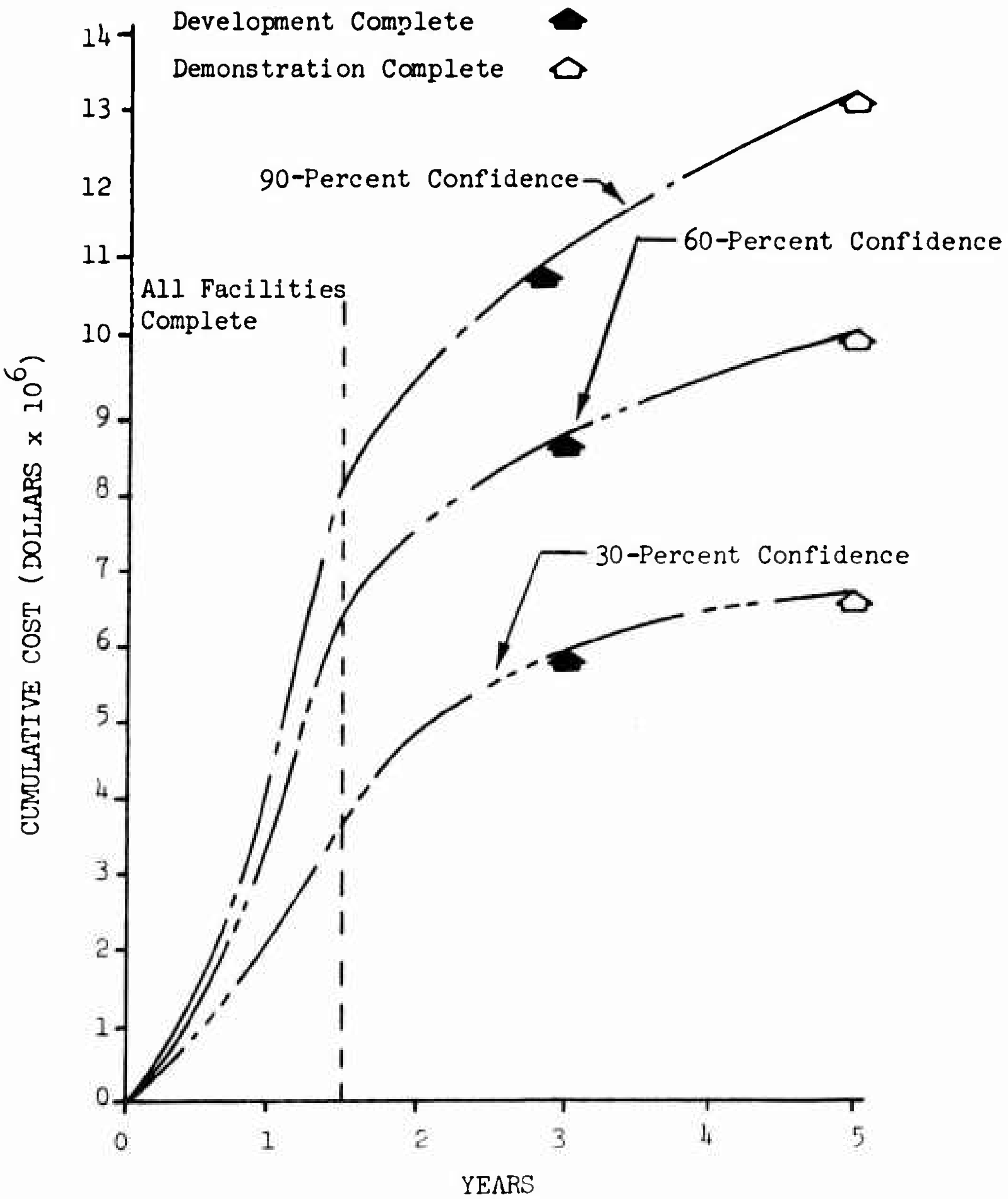


Figure 61. Demonstration Test Hour Versus Required Component True MTBF.



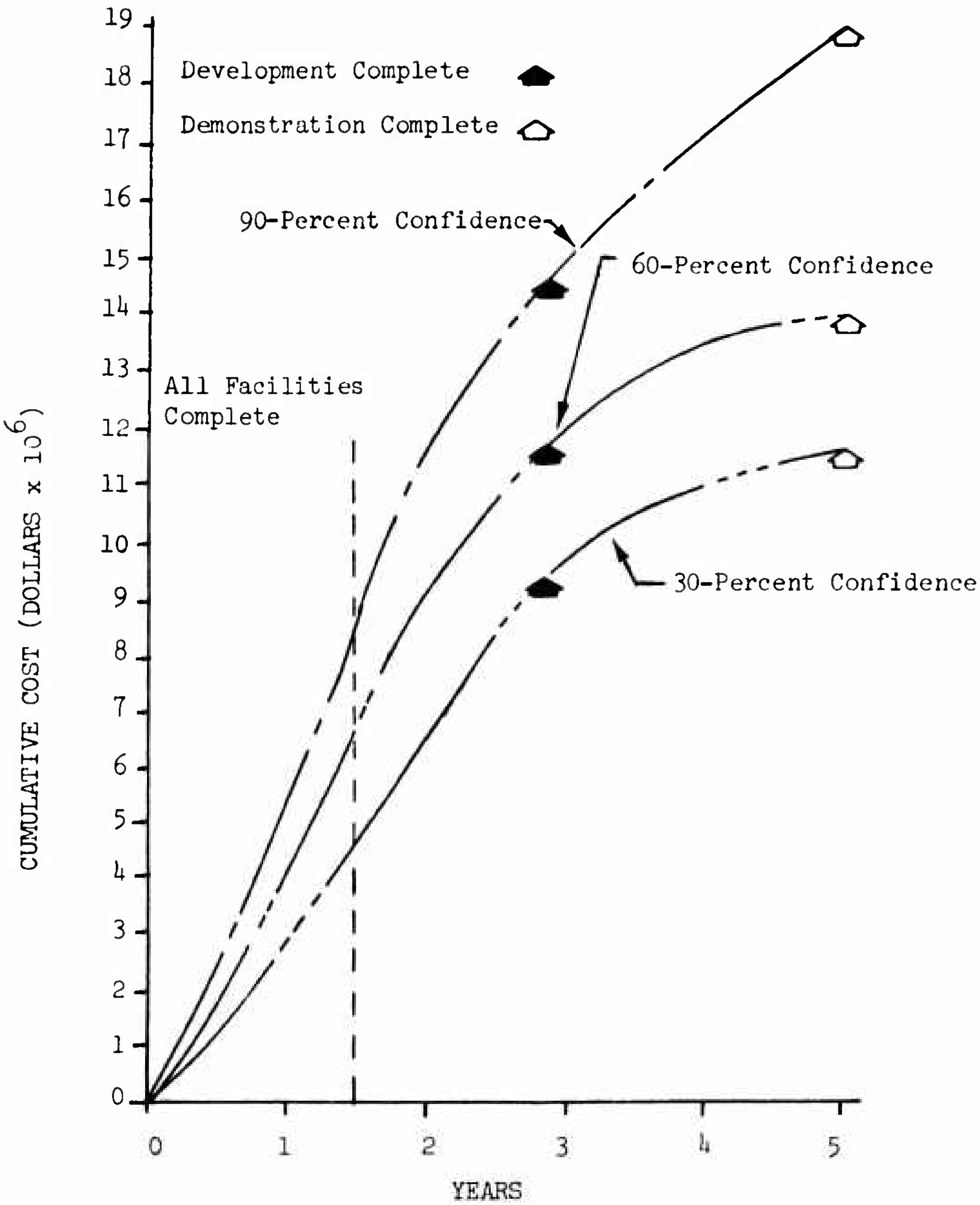
Note: Facility dollars do no include cost of aircraft parts except that tiedown vehicle(s) costs are included at one million per vehicle.

Figure 62. Cost Versus Time At 500-Hour MTBR.



Note: Facility dollars do not include cost of aircraft parts except that tiedown vehicle(s) costs are included at one million per vehicle.

Figure 63. Cost Versus Time At 1000-Hour MTBR.



Note: Facility dollars do not include cost of aircraft parts except that tiedown vehicle(s) costs are included at one million per vehicle.

Figure 64. Cost Versus Time At 1500-Hour MTBR.

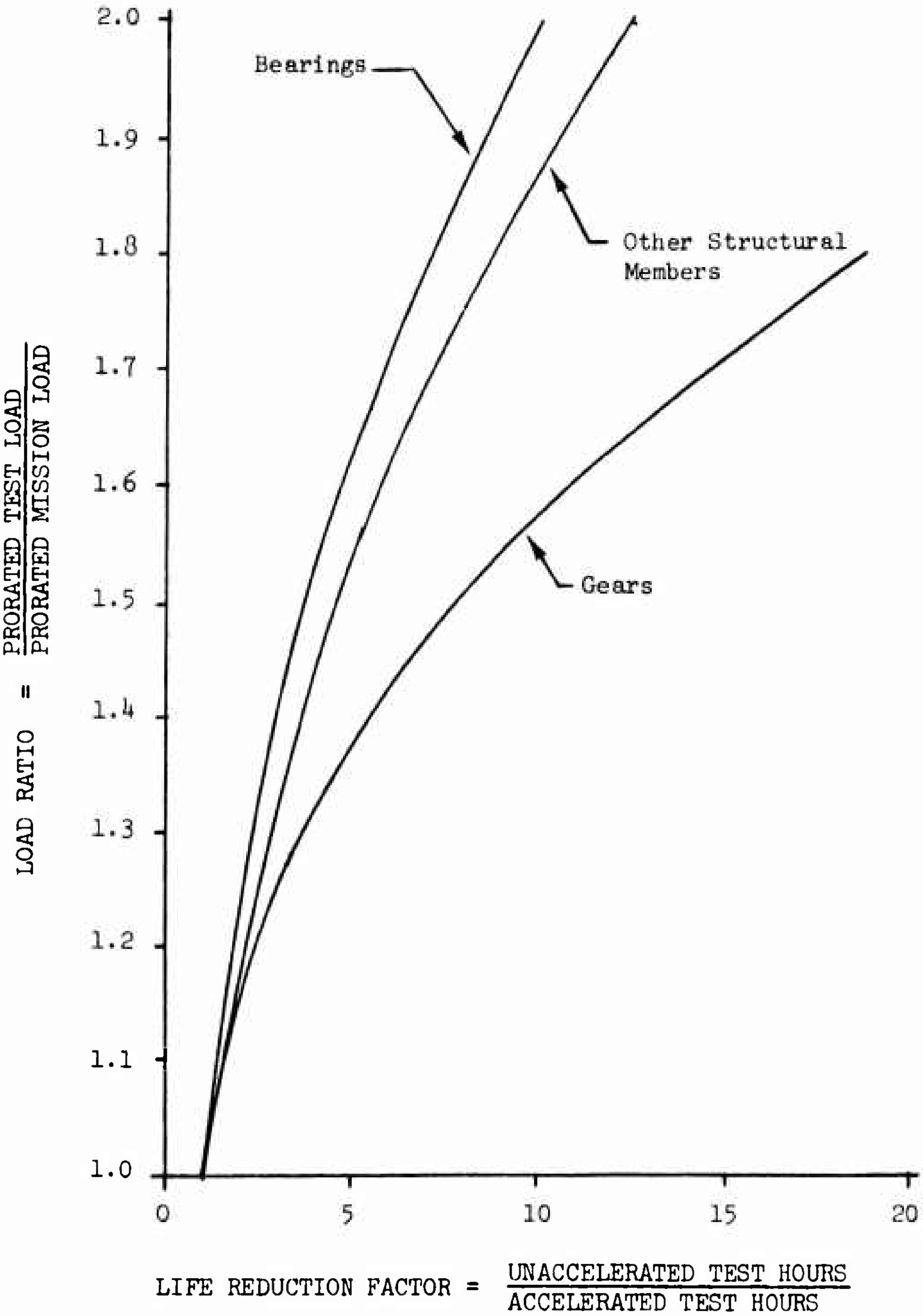


Figure 65. Load/Life Relationship.

SAMPLE TEST PROGRAM

INTRODUCTION

The following paragraphs outline a sample reliability test program for the development phase of the helicopter. This program shows the relationship between all components, subsystem and system tests to demonstrate an MTBR for all rotors and transmission systems of 500 hours at a confidence level of 60 percent. Sixteen hundred hours of demonstration testing is required as shown in Figure 56 of the trade-off studies section and the plan outlined in Figure 66. This 1600 hours, which will be conducted on the PSTB and tiedown aircraft tests, permits a total of two failures in each system. In this sample program, an additional 300 hours of tiedown development testing is included over the testing outlined in the trade-off studies. This plan is essentially the sequential test plan selected for the trade-off studies of the previous section. This program may be somewhat idealized and may require "tailoring" to suit the requirements of a particular helicopter program. It will, however, provide a guide for establishing development and demonstration requirements for transmission and rotor systems for future U.S. Army helicopters as well as provide adequate demonstration of proposed modifications to current aircraft. The cost curves for this plan can be constructed from the average number of test hours per month in Table XI, the average cost data in Table XII, and the test plan schedule, Figure 66.

PROTOTYPE AND DESIGN SELECTION TESTS

Description of Test Setup

Prototype and design selection tests include the following:

(1) Experimental Stress Analyses. These tests are used to verify stress analyses, to optimize structural design, or are used where the component complexity may not lend itself to theoretical analysis. The approach is to make a photoelastic plastic or metal model or a full-scale prototype of the part and subject it to a loading condition indicative of the expected service. From this, stress patterns of alternate designs may be obtained and compared to select the best structural design.

(2) Model Fatigue Tests. These tests have the same purpose as photoelastic testing with two exceptions: the loading is dynamic, and some environmental conditions may be introduced. The actual test setup would vary, depending upon what part was being tested, but since primarily flight-critical rotor head parts would be tested, most test setups would resemble the present approaches used on rotor head component structural tests in a scaled-down version.

(3) Design Selection Tests. These tests could include such typical tests as abrasion strip tests, bond separation tests on blade pockets, and nonstructural aerodynamic surface fatigue tests.

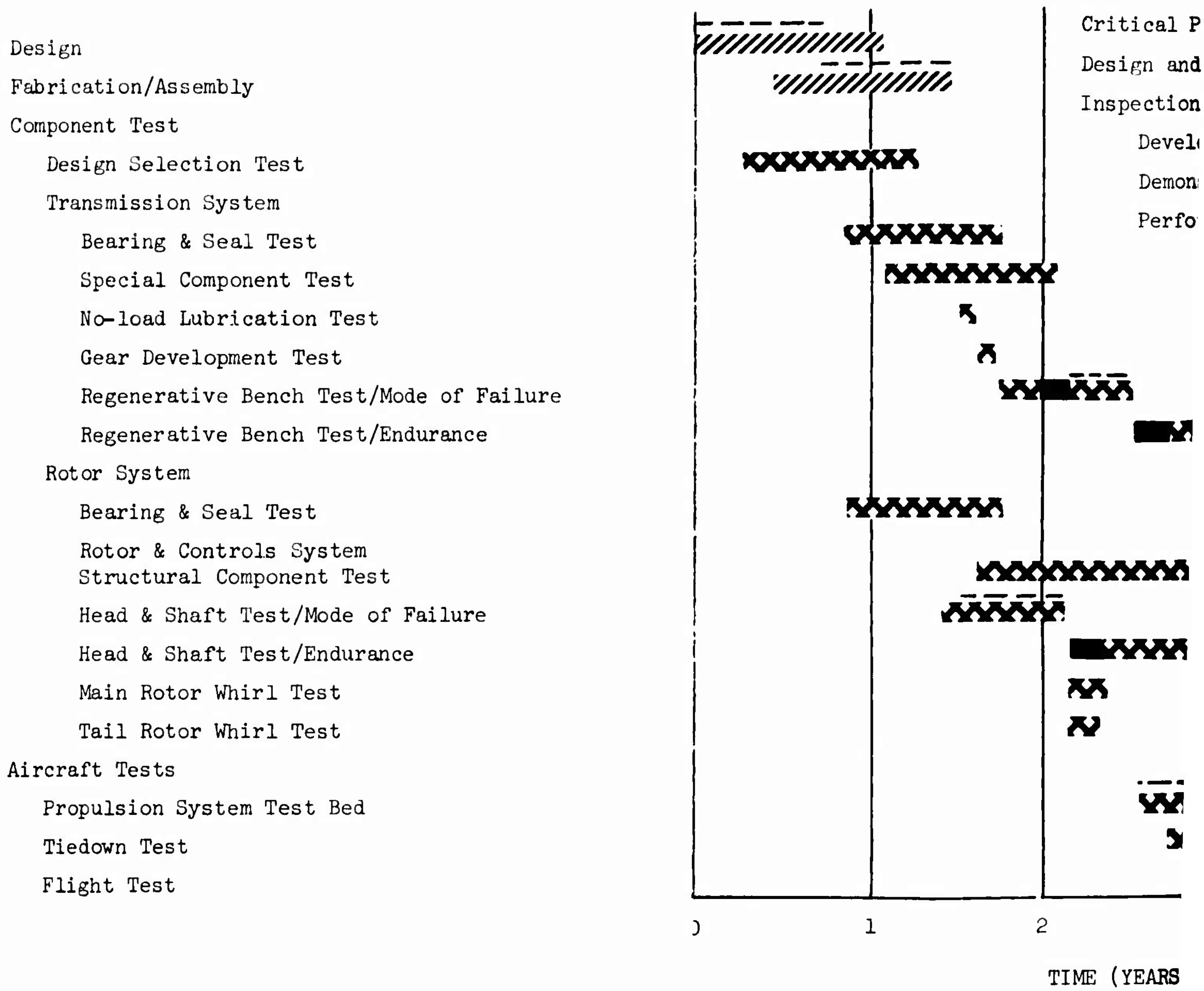
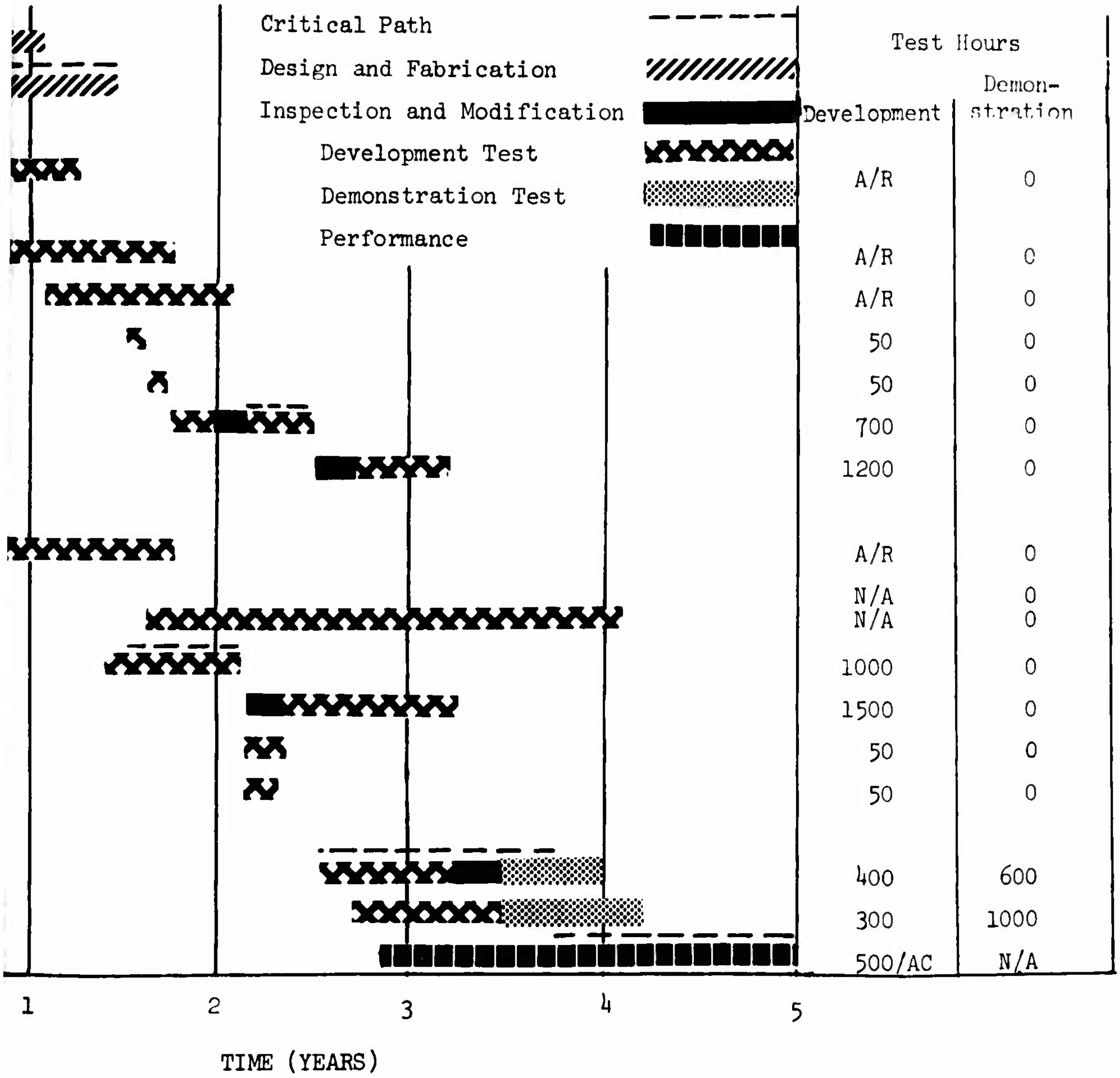


Figure 66. Sample Test Plan Schedule.


Critical Path
Design and Fabrication
Inspection and Modification
Development Test
Demonstration Test
Performance
Test Hours
Development
Demon-stration
A/R 0
A/R 0
A/R 0
50 0
50 0
700 0
1200 0
A/R 0
N/A 0
N/A 0
1000 0
1500 0
50 0
50 0
400 600
300 1000
500/AC N/A
1
2
3
4
5
TIME (YEARS)

Acceptance and Rejection Criteria

In the three cases described, the tests will select the best of several possible designs and indicate different possible structural modes of failure. As such, there are no absolute rejection criteria for specimens at this early stage.

BEARING AND SEAL TESTS

Description of Tests

Seals will be tested under environmental conditions and subjected to simulated wear and angular displacements of mating parts. Bearings will be tested under similar conditions, including sand, dust, corrosives, and lack of lubrication. Bearings will be loaded and supported in a fashion similar to that experienced in service. Motion will be reciprocating, rotating, or axial as required by the particular application. The facility will be capable of testing prototype and production seals and bearings.

Acceptance and Rejection Criteria

In the case of seals, the criteria are based on measured leakage and time to deteriorate to unacceptable levels of leakage. In the case of bearings, the criteria are based on time required to cause a bearing failure where failure is defined by the presence of spalling, fatigue cracks, and pitting.

TRANSMISSION SPECIAL COMPONENT BENCH TESTS

A typical arrangement for this test would consist of a regenerative loop in which the particular transmission subassembly is loaded. Both operating speed and load will be accelerated during portions of the test to reduce test time, reduce cost, and detect modes of failure early in the development program. Typical subassemblies that might be considered for such testing include planetary gearing, high-speed input gearing, and freewheel units.

Acceptance and Rejection Criteria

Since this is a development test, it will be terminated when sufficient contractor confidence exists that the MTBF of the subassembly is sufficient to meet the objectives of the development program.

TRANSMISSION SYSTEM TESTS

These tests are outlined in the following paragraphs and include no-load lubrication tests, regenerative mode of failure tests, gear pattern development, and regenerative endurance bench tests.

No-load Lubrication Test

In this test, the gearbox is run at various speeds up to 120 percent of normal operating speed at the various attitudes expected during service to

establish that the lubrication system functions properly, to determine full and refill levels in the reservoir, and to determine the power losses of the gear train.

Acceptance and Rejection Criteria

The transmission must run without overheating and no evidence of churning should exist.

Gear Pattern Development, Full-Load Efficiency Tests

In this test, the gearbox is run at 3/4 and full torque at 100 percent speed to check the contact on the various gear meshes. The gearbox is then covered with a thermal insulating blanket, and the full load efficiency is determined by measuring the temperature and oil flow through a heat exchanger.

Acceptance and Rejection Criteria

Special coating applied to the gear teeth will display, after run up, uniform tooth loading without evidence of local load concentrations in accordance with accepted gear standards.

Regenerative Mode of Failure Tests

The transmissions in these tests are run as part of a closed regenerative loop. Often the inputs of two main transmissions are coupled together as are the output shafts in other closed loops. These circuits are completed by using large commercial gearboxes in combination with modified aircraft gearboxes as shown in Figure 67. The gear train is loaded by introducing torque into the regenerative loop and then is brought up to speed. Thrust loads and sometimes head moments are introduced into the main rotor shaft loop. Torque, thrust, and rotational speed are often accelerated over normal values for portions of the test. The preload or locked-in torque, together with speed of rotation, indicates that power and the torque values are varied to produce a spectrum of loading more severe than the anticipated flight loading. For this particular test, a life acceleration factor of 4 to 4.5 would be used. Such accelerated testing is designed to detect weaknesses in the transmission system in a relatively short period of time, providing a maximum amount of time to redesign the weak links thus discovered. When contractor confidence in the transmission is sufficient, the next phase of testing is started. These techniques also apply to the intermediate and tail rotor gearboxes used in the transmission system.

Acceptance and Rejection Criteria

Since this is a development test, it is terminated when sufficient confidence exists that the MTBF of the transmission is sufficient to meet the program requirements.

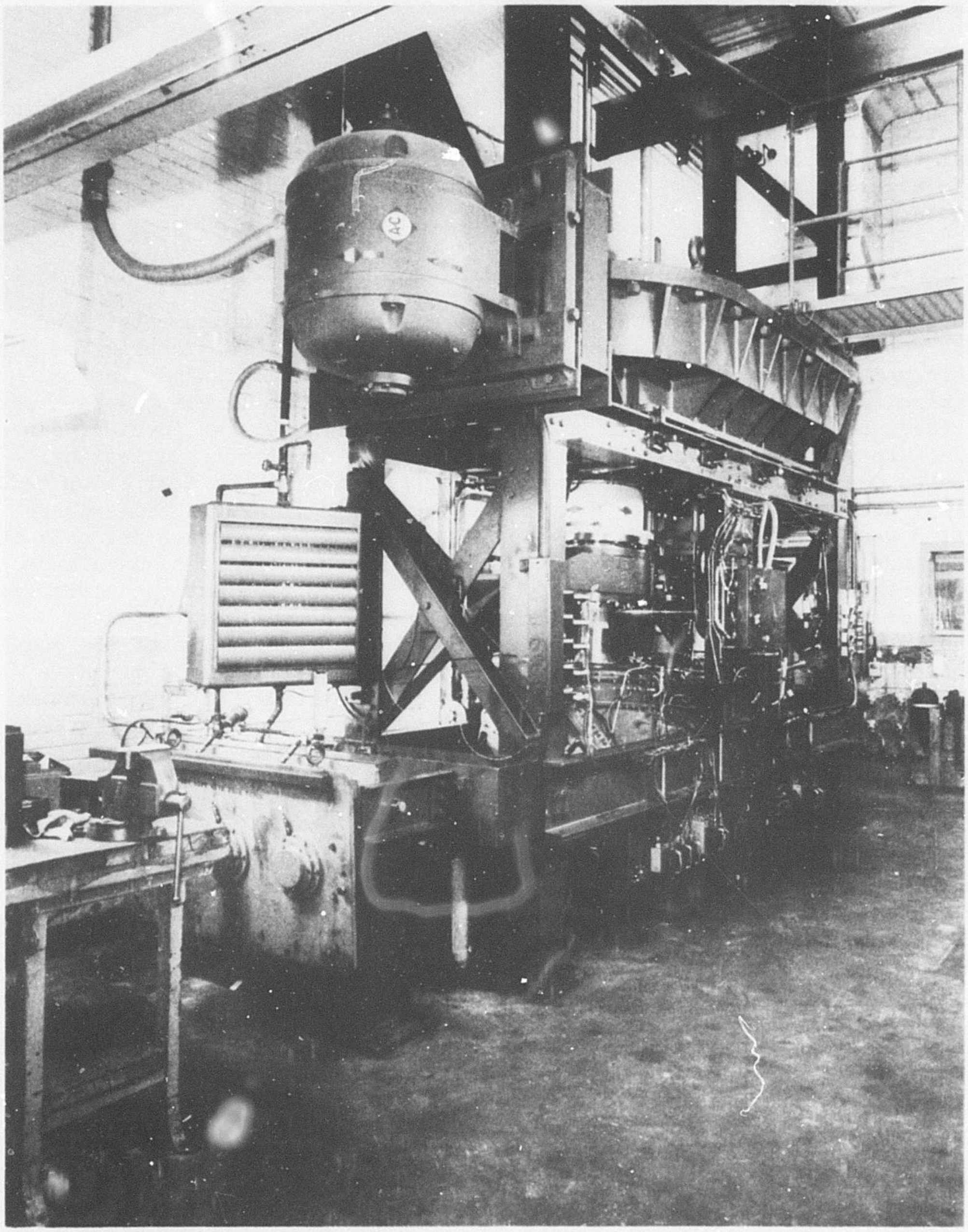


Figure 67. H-3 Main Gearbox Regenerative Test Stand.

Regenerative Endurance Bench Tests

The tests use the same facility as the previous tests except that the acceleration factors are reduced to 2.0 or thereabouts.

Acceptance and Rejection Criteria

The gearbox functions properly in all respects and has accumulated sufficient time at the accelerated powers with two or less failures so that when test time is converted to equivalent aircraft time (i.e., test hours times life acceleration factor), an MTBR is demonstrated that meets the program requirements.

ROTOR AND CONTROLS STRUCTURAL COMPONENT TESTS

The purpose of these tests is to demonstrate safety of components. These test setups vary depending upon application, but all setups consist of five basic parts: a test article suitably instrumented, a loading device or machine, a support fixture to hold the test article while being subjected to load, a measurement system usually for load or stress and cycles, and a failure warning system to allow for post crack detection and testing. Between one and three components are usually tested in one test setup under highly accelerated single or multiple level testing. Many specimens are tested for each setup during subsequent tests. Tests indicate not only the structural reliability of the part, which is several orders of magnitude higher than the requirements of the test of the program, but the different modes of failure to be expected for a given component. The tests are usually used to demonstrate the safe-life or fail-safe nature of the component from the standpoint of long crack initiation time, long crack propagation time, adequacy of failure detection systems, and verification of multiple load paths. Typical test installations are shown in Figures 68, 69, and 70.

Acceptance and Rejection Criteria

The test data is used to generate mean S/N curves for the component. By applying strength reduction factors to the mean curves, working stress levels are obtained; and based upon flight spectrum loads, the tests demonstrate that the part has the required reliability.

Head and Shaft Tests

The facility will test the entire rotor head, including the inboard portion of the blade, the rotating con ~ol system, and the transmission output shaft. Loads and motions will . present flight conditions and will be independently variable and programable. In addition, service environmental conditions will be applied, including salt water spray, dust, sand, water spray, humidity, and temperature. While loads and motions will be accelerated depending on test, environmental conditions will be accelerated as applicable. The tests will consist of mode of failure and endurance testing described below, conducted on a test stand similar to that shown in Figure 71.

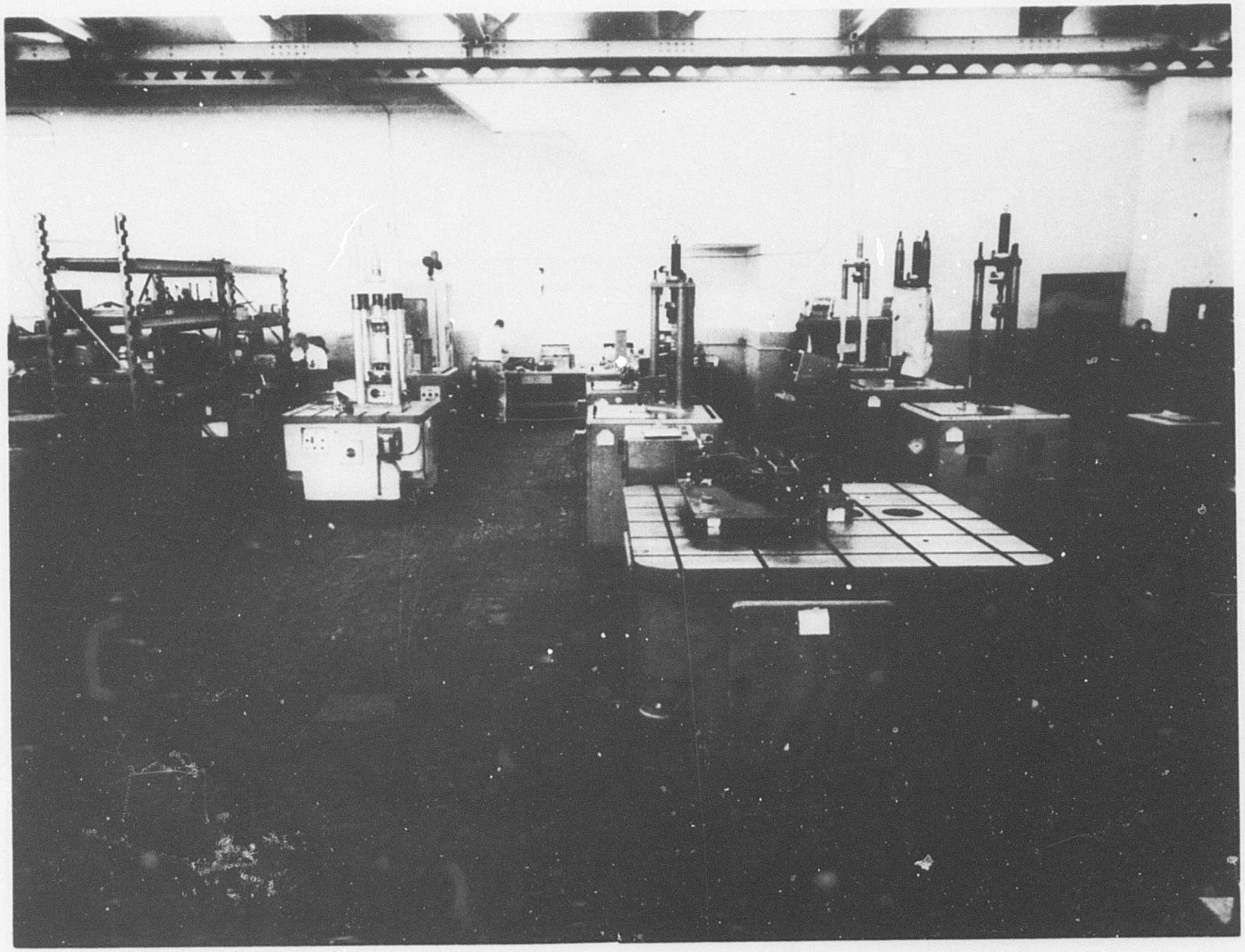


Figure 68. Structural Reliability Fatigue Laboratory Shaker Tables.

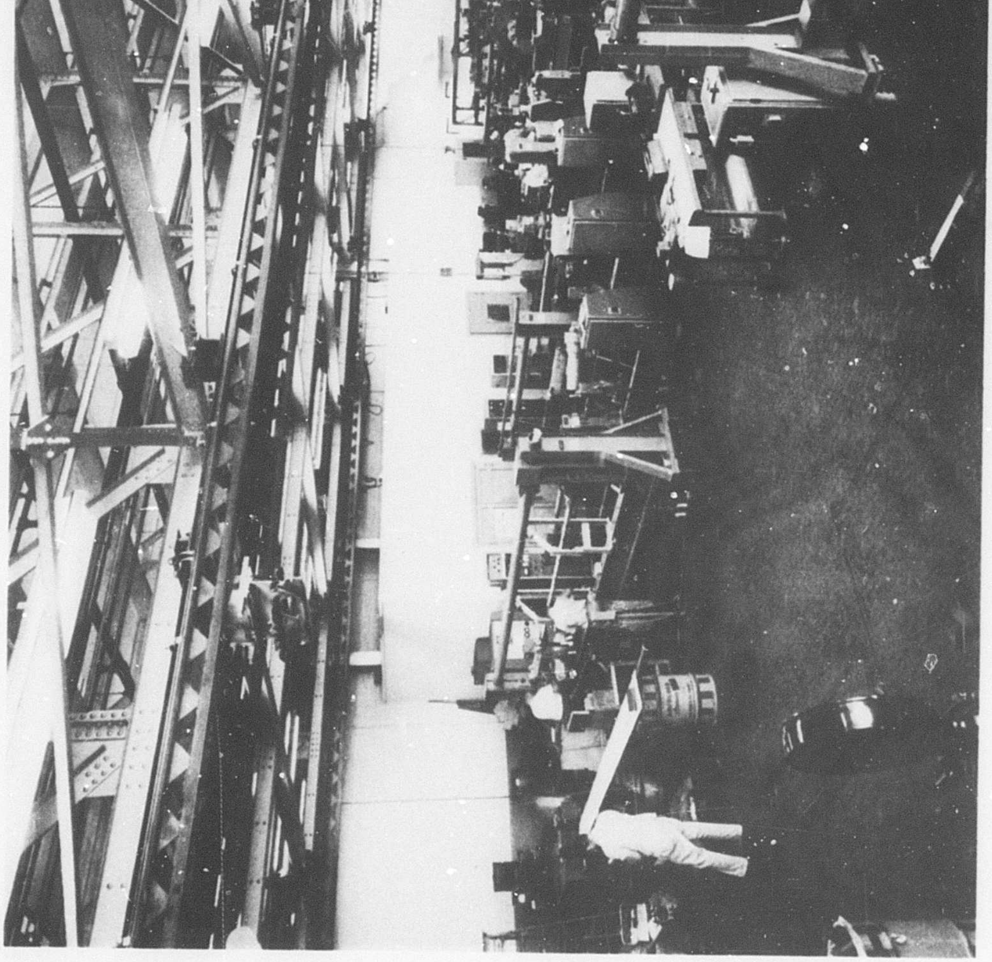


Figure 69. Structural Reliability Fatigue Laboratory.

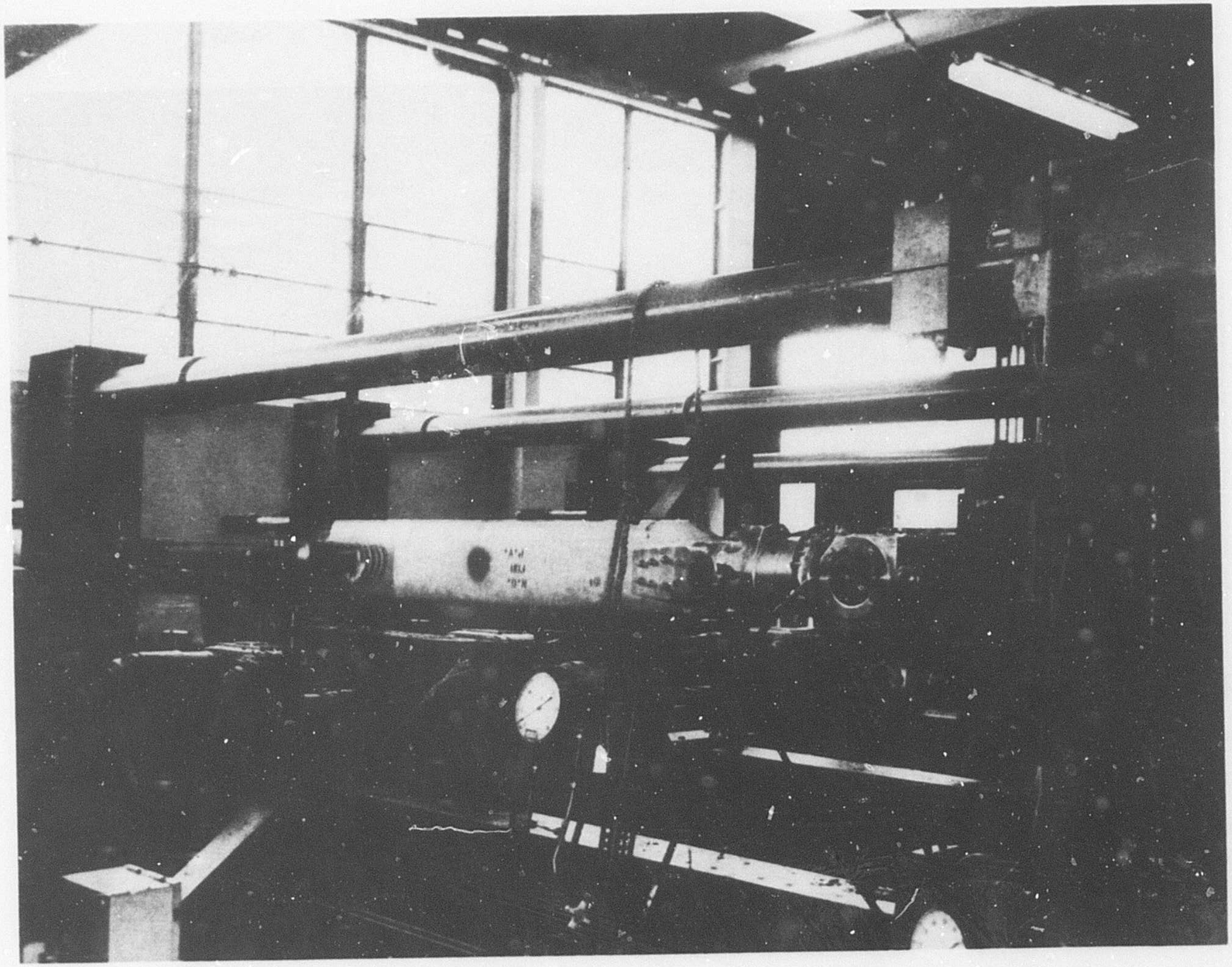


Figure 70. H-3 Fatigue Test of Main Rotor Inboard Spar Section.

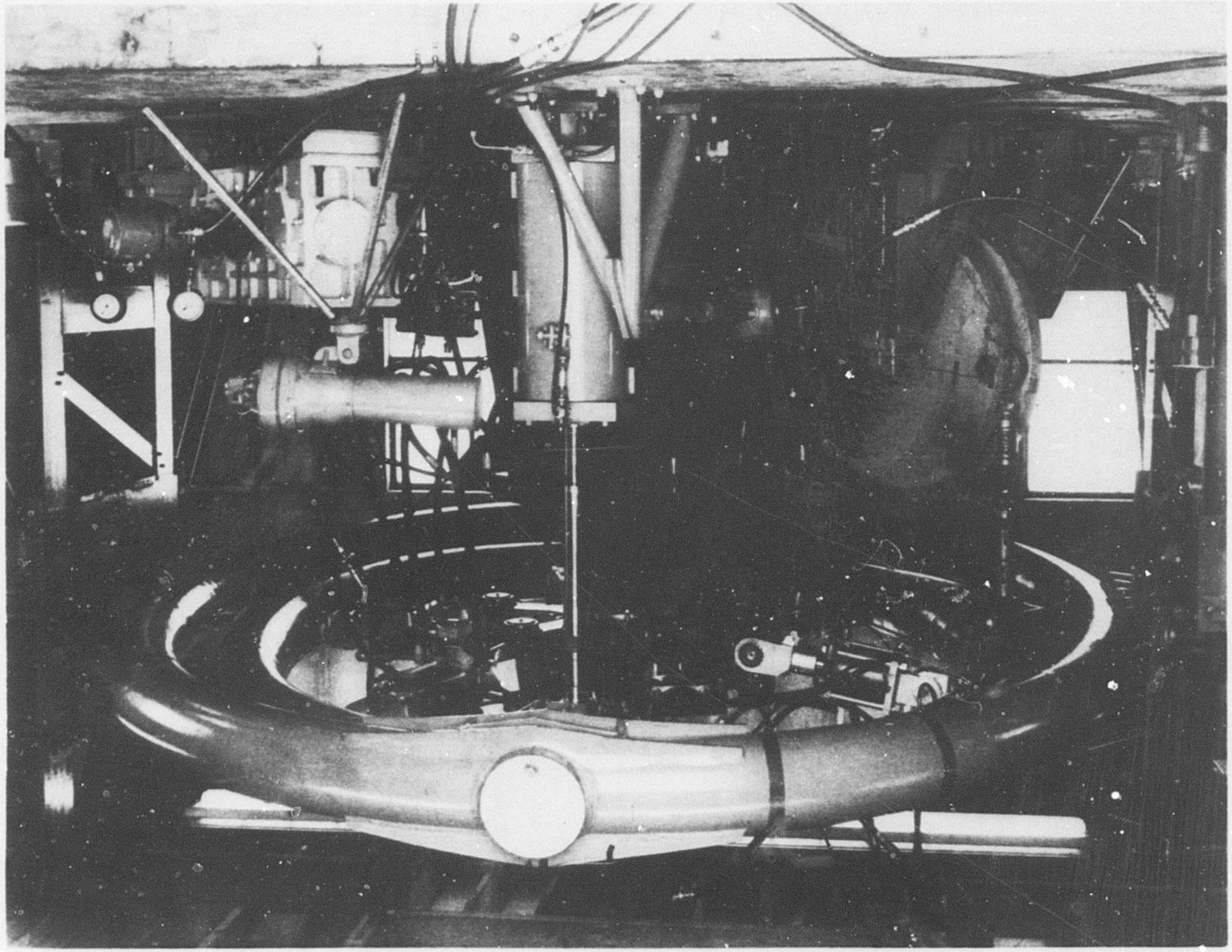


Figure 71. H-3 Main Rotor Head and Shaft Fatigue Test Facility.

Mode of Failure Tests

These are structural tests in which the loads and motion are highly accelerated in order to uncover the weak links in the rotor head in a short time interval. Failure modes and extent of observed wear provide data to estimate reliabilities of fatigue strength, bearings, seals, etc. If the estimates indicate that the required reliability may not be advanced, the part is redesigned and retested. At the completion of these tests, there is a high degree of confidence that the rotor head will be free of major problems when subjected to endurance tests to demonstrate the required MTBR and structural reliability under simulated environments.

Rotor Head MTBR and Structural Substantiation Endurance Test

These tests are conducted to demonstrate an acceptable rotor head MTBR and provide final structural substantiation under total environmental conditions. In order to achieve both objectives simultaneously, the rotor head will be subjected to a combination of accelerated loads, motions, and speed under simulated environments. Acceleration levels will be substantially lower than those used for mode-of-failure testing, yet high enouth to verify structural reliability when appropriate strength reduction factors are applied. Required test time is shortened by both load and speed acceleration factors. An example of using mode-of-failure testing prior to these tests is shown in Figure 72. The rotor head is subjected to a load acceleration of approximately 2.5 times maximum flight load for mode of failure Test 1. Early failures show that the working strength intersects the flight loads. Redesign was made, and Test 2 indicates that working strength does not intersect flight loads. The rotor is then subjected to endurance testing at load levels significantly lower than the mode of failure test, but high enough such that if failure occurs the working strength will not intersect flight loads.

Acceptance and Rejection Criteria

Use test data to generate mean S/N curves for the component. Apply strength reduction factors to the mean curves to obtain working stress levels, and with flight spectrum loads, demonstrate that the part has the required reliability. In addition, the entire rotor head must have functioned for a sufficient time under environmental conditions simulating service to demonstrate the required MTBR.

MAIN ROTOR AND TAIL ROTOR WHIRL TESTS

Description of Tests

The setup consists of a complete rotor head and controls which are rotated at normal operating speeds on a whirl tower, such as is shown in Figure 73. The tests which are performed include stresses induced in the rotor head and blades by various motions (coning and flapping), natural frequency determination, and aerodynamic performance tests.

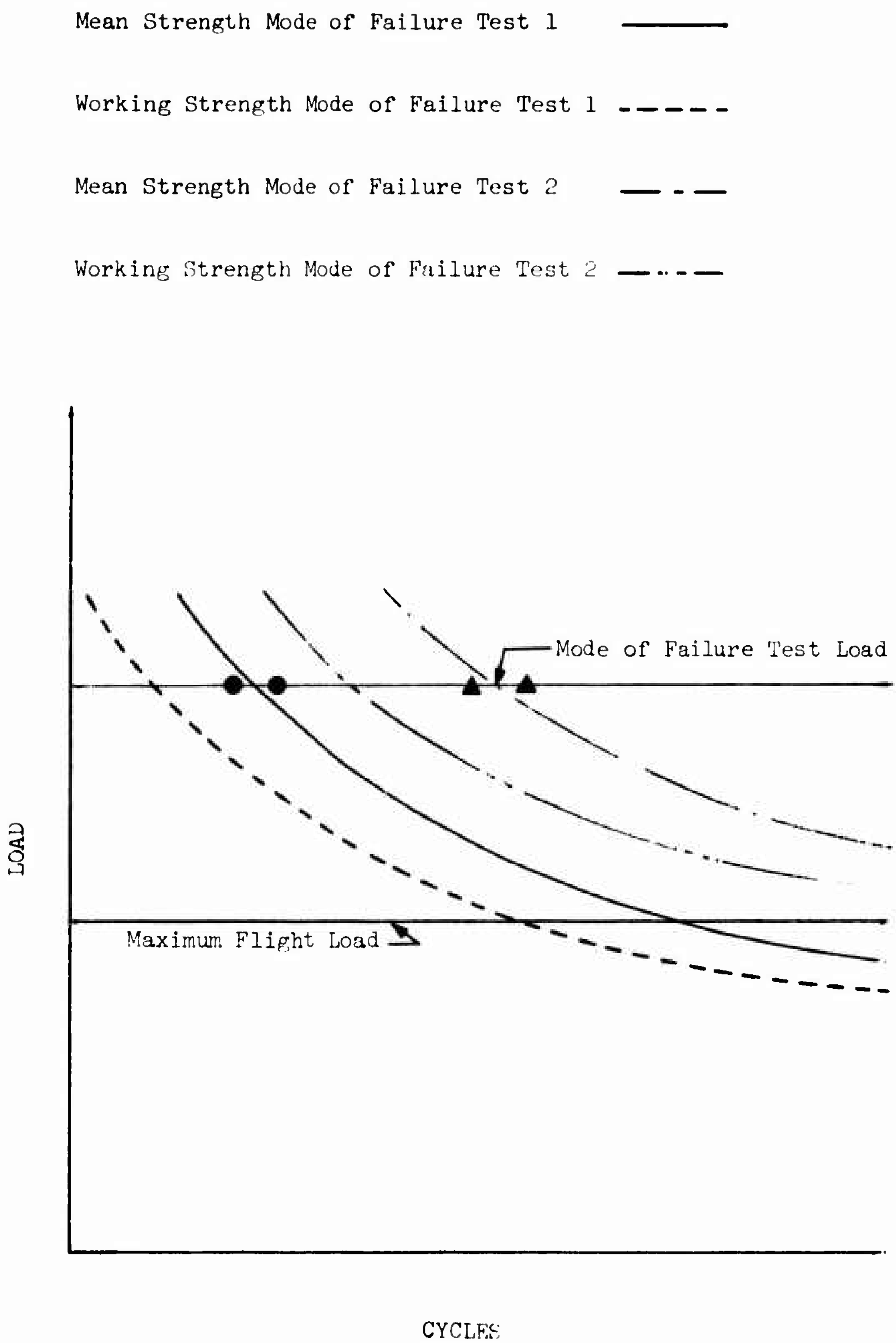


Figure 72. Effect of Mode of Failure Tests on Development.

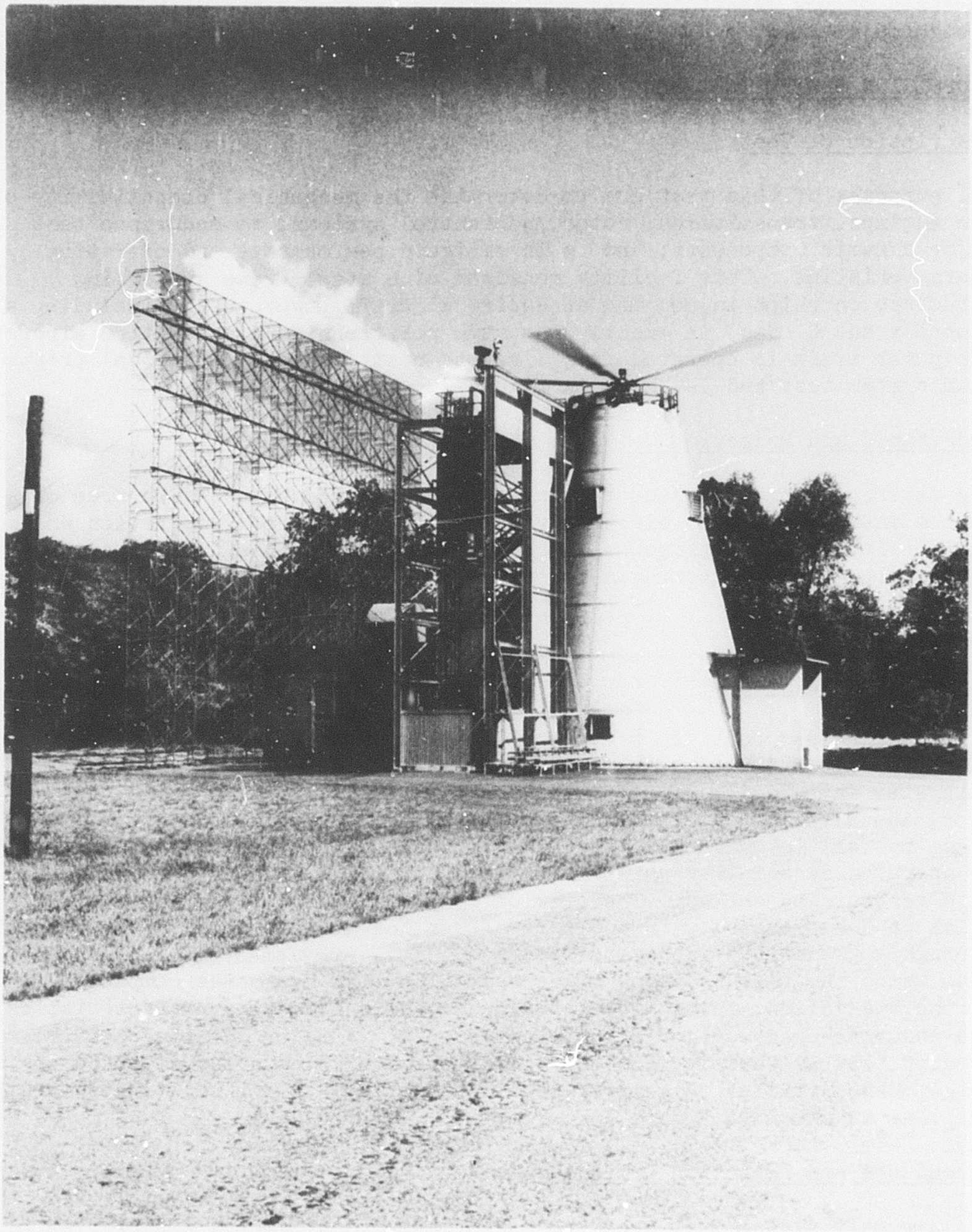


Figure 73. 8000-Horsepower Main Rotor Whirl Stand.

Acceptance and Rejection Criteria

In each case, the rotor head must be structurally sound, having no instabilities and no resonances near aircraft operating frequencies; must have stresses of low magnitude; and must perform in accordance with aerodynamic design objectives.

PROPULSION SYSTEM TEST BED

Description of Test

The purposes of this test are to determine the mechanical compatibility of the engines, transmission, rotor and control systems; to endurance test major dynamic components; and to investigate performance and operating characteristics. This facility consists of a steel-frame supporting structure on which is mounted an entire aircraft power train (including all controls and blades) in exactly the same positions as a production aircraft. The power train is operated from a remote control room. A typical propulsion system test bed is shown in Figure 74.

Acceptance and Rejection Criteria

The entire system must meet the performance requirements and be free of system interaction problems that would impair the overall operation and reliability of the components. The system must evidence an MTBF commensurate with that demonstrated for the major subsystems.

TIEDOWN TEST

Description of Test

The tiedown test uses the first complete aircraft system produced and provides the closest step to actual flight testing. This test provides for subsystem integration of not only the power train components but, in addition, the airframe, electrical, communication, and all utility systems. These are all interfaced in the real airframe environment. The aircraft is operated dynamically while it is literally tied down to the ground pad with restraining cables. The crew on board manipulates all those systems which can be operated with the aircraft on the ground, putting the aircraft through a prescribed operating spectrum. Data are measured in the aircraft room where the test is being monitored. The test evaluates compatibility of the subsystems, investigates performance and operating characteristics, and endurance tests major dynamic components. A major advantage of the tiedown test is that it permits relegation of problem areas detected on flight test articles to a lower level of testing. A typical tiedown test facility is shown in Figure 75.

Acceptance and Rejection Criteria

The aircraft system must meet the performance requirements and be free of system interaction problems that would impair the overall operation and reliability of the components. The system must evidence an MTBF

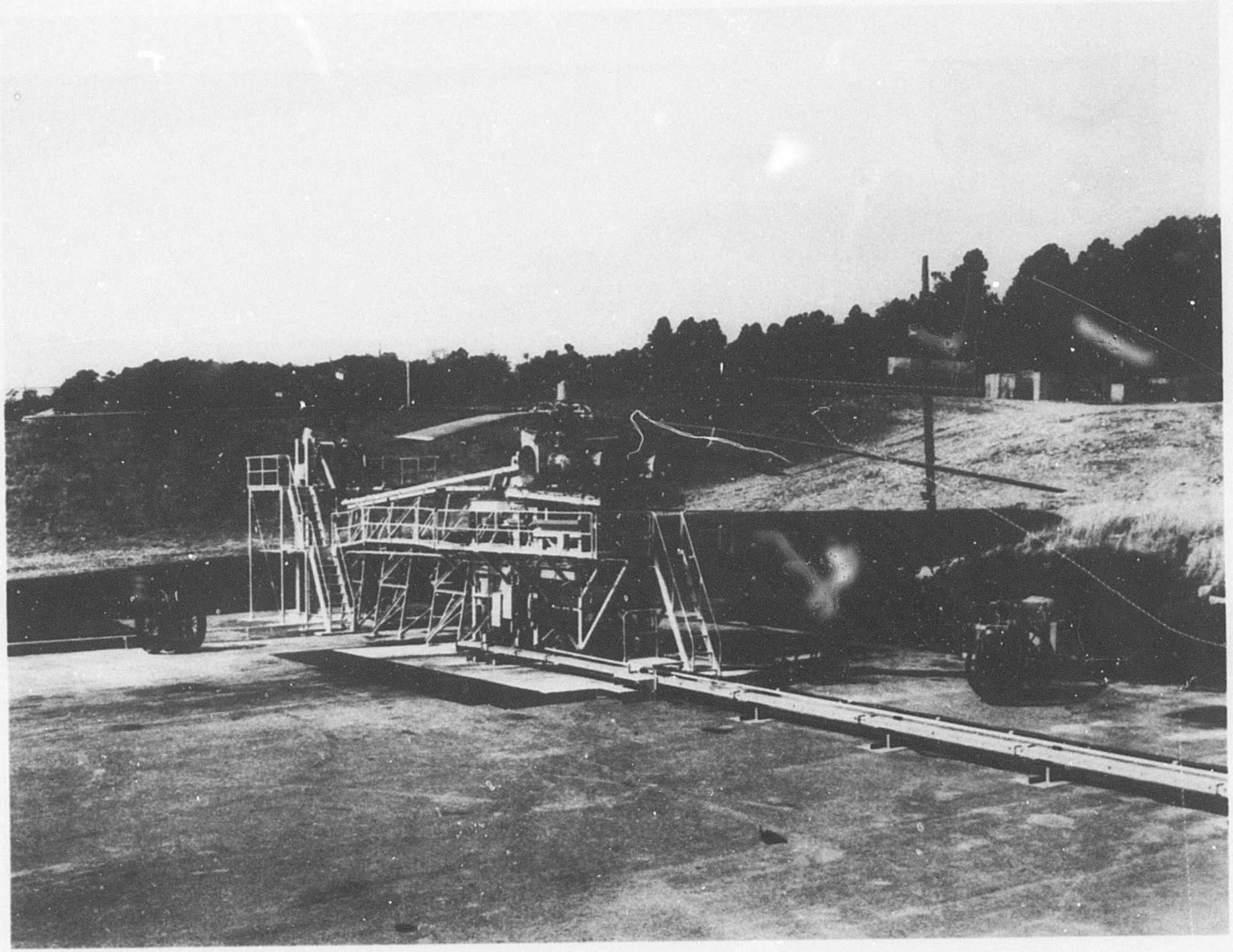


Figure 74. H-54 Propulsion System Test Bed.

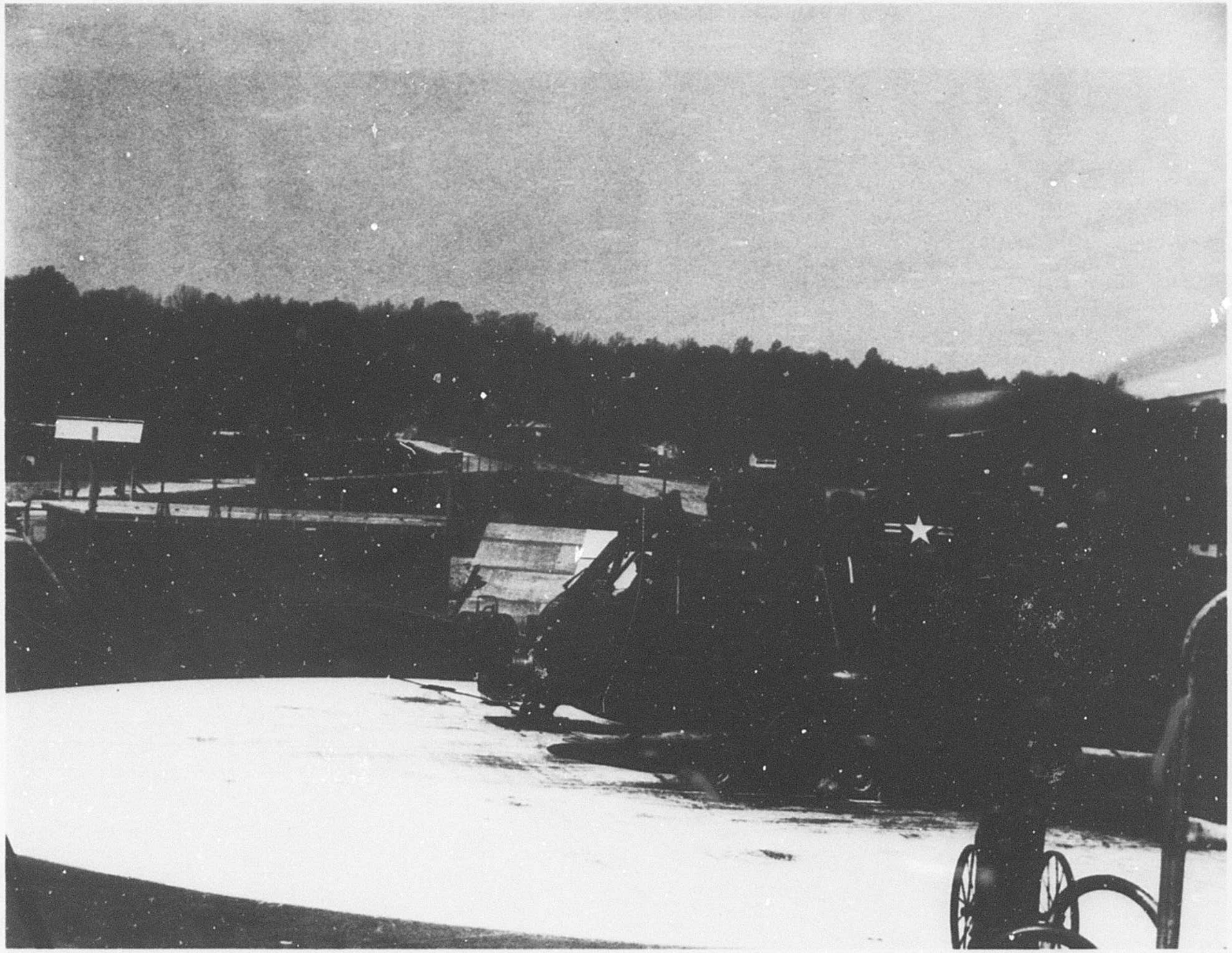


Figure 75. H-3 Tiedown Aircraft.

commensurate with that for all the major subsystems in the tiedown aircraft.

FLIGHT TEST

The helicopter flight test program should be designed to complete the contractors and contractual aircraft handling qualities, performance, and structural buildup programs in a minimum number of flight hours and in the shortest possible calendar time. In addition to the necessary survey test flights to determine stress and vibration levels, etc., training and classical procedures of flying at incremental changes in airspeed, and the effects of various centers of gravity, a portion of the flight test program should be devoted to flying simulated missions. Data obtained from these tests can be used to verify the design mission spectrum and to verify the operation and maintainability of the dynamic and airframe components under conditions approaching actual service operation.

SUMMARY

Various types and combinations of tests are included in the sample test program to adequately develop the dynamic systems in a timely manner. To summarize the combined test program, Table XV lists the effect of the various tests upon the overall program costs and the associated components that are required to conduct the sample test program. The foregoing sample reliability test program is primarily applicable to a single main rotor/single tail rotor configuration helicopter with typical design parameters as listed in Table XIV.

TABLE XIV. AIRCRAFT DESIGN PARAMETERS

Item	Value
Gross Weight, pounds	15,000
Main Rotor Diameter, feet	60
Tail Rotor Diameter, feet	10
Engine Horsepower	2,500
Number of Main Rotor Blades	4
Number of Tail Rotor Blades	4
Transmission System	
Main Gearbox	1
Intermediate Gearbox	1
Tail Gearbox	1

TABLE XV. SUMMARY OF SAMPLE T

	Test Hours		Model Sub-assemblies	Production or Prototype Sub-assemblies	Main Rotor Heads
	Develop-ment	Demon-stration			
Component Test					
Design Selection Test	A/R	0	10	3	1
Transmission System					
Bearing and Seal Test	A/R	0			
Special Component Test	A/R	0		8	
No-load Lubrication Test	50	0			
Gear Development Test	50	0			
Regenerative Bench Test/Mode of Failure	700	0			
Regenerative Bench Test/Endurance	1200	0			
Rotor System					
Bearing and Seal Test	A/R	0			
Rotor and Controls System Structural Component Test	N/A	0		4-6	
Head and Shaft Test/Mode of Failure	1000	0			1
Head and Shaft Test/Endurance	1500	0			1
Main Rotor Whirl Test	50	0			1
Tail Rotor Whirl Test	50	0			
Aircraft Tests					
Propulsion System Test Bed	400	600			2
Tiedown Test	300	1000			1
Flight Test	500/A/C	N/A			A/R

Note: (1) Plus 2 Dummy or Slave Gearboxes.

Preceding page blank

LE XV. SUMMARY OF SAMPLE TEST PROGRAM

Production or Prototype Sub-assemblies	Main Rotor Heads	Tail Rotor Heads	Main Rotor Blades	Tail Rotor Blades	Seals	Bearings	Transmissions	Complete Aircraft
3	1	1	4	4				
					40	60		
8								
							1	
							1	
							2[1]	
							2[1]	
					40	60		
4-6			4-6					
	1	1						
	1	1						
	1		4					
		1		4				
	2	2					2	
	1	1					1	1
	A/R	A/R					A/R	A/R

RECOMMENDED TEST PLAN

INTRODUCTION

The following presents a recommended development and demonstration test program for helicopter transmission and rotor systems components. The test program is designed to provide for adequate development of the dynamic components as well as to demonstrate that the design requirements (derived from the aircraft mission requirements) for safety, reliability, and maintainability have been met. This program is considered to be the minimum program necessary for current helicopter dynamic component development. It demonstrates with accelerated testing an MTBR of 1000 hours at 60 percent confidence for a component if two or less failures are exhibited.

DISCUSSION

To achieve a high degree of component reliability, the program must include provisions for making expeditious modifications to the test components as well as the initial production units (if production must be concurrent with prototype development - as it so often is). The ability to make modifications early in the program without lengthy evaluation and approval cycles (such is common with many of the current engineering change proposal procedures) is as important to the overall goal - improved helicopter dynamic component reliability - as a properly designed and executed test program.

The early phases of transmission development testing should be directed toward uncovering the major modes of failure and demonstrating that the failures/malfunctions are noncatastrophic and fail-safe and can be detected by the inspection and detection techniques to be used in service. This objective can be best accomplished by "overstress" bench tests on the initial transmission, running the gearboxes at the upper level of their proposed operating spectrum (i.e., takeofff rating or slightly above). It should be recognized that some portion of this test should be conducted at lower power levels to check lubrication and vibration, as well as to avoid scuffing and scoring of helical and bevel gearing. The operation of the gearboxes at powers well in excess of the normal operating schedule can produce results that are not meaningful. The load acceleration used in development (and endurance) tests should be kept within practical limits, acceleration of power, speed, thrust, and load are approximately as follows:

Power	110 percent to 120 percent of takeoff or maximum rating
Speed	110 percent of maximum speed
Thrust, Load	120 percent of maximum anticipated conditions

The operation of components at loads beyond these limits may produce excessive deflections. These components, therefore, may be operating beyond the point where the anticipated life-load relationships apply.

Preceding page blank

To demonstrate a component requirement of 1000-hour MTBR at 60-percent confidence requires 4000 hours of demonstration testing and no more than two failures, as established with Figure 56. A corresponding 4000 hours of development testing are required to debug the component and to establish a sufficiently adequate MTBF to reasonably assure that the demonstration goal is obtainable. The use of several mode-of-failure test runs and a development test where the loads are accelerated will result in a reduction of the number of development test hours and the calendar time. The acceleration of loads suggested is that level to produce a life acceleration factor of four (using the cumulative damage approach) over the aircraft mission requirements on a prorated basis. This approach will effectively reduce the number of development test hours, in the author's opinion, to about half of that necessary to achieve the same MTBF by unaccelerated testing. A similar approach can be taken during the demonstration test phase.

The test plan of Figure 76 was designed using this accelerated approach.

Transmission Bench Test

A minimum of two test gearboxes should be subjected to the bench tests generally described in the following paragraphs. A test time accumulation of 50 hours on one gearbox should be completed prior to start of a Propulsion System Test (or tiedown test).

1. A 200-hour overstress development test with 75 percent of the test time being at takeoff power* or equivalent, 15 percent of the time at 110 percent of takeoff power, and the remaining 10 percent at normal cruise power. All other test time at powers required for cooling, etc., between takeoff or better power increments should not be credited toward the total 200 hours.

   The test objective is to determine the modes of failure, the detectability of failures, and the extent of fail-safe features. In addition, the program should be used for the incorporation and evaluation of fixes and in general to "debug" the transmission. The requirement is not to "pass" this test but to evaluate the design and compare its performance to the design requirements.

2. Upon completion of the initial 200-hour overstress development test (or major malfunction of the test box), another 200-hour overstress bench test should be conducted on a second gearbox which incorporates all modifications suggested by the initial test. (The fabrication of "fixes" and improved items should be initiated while the first test program is in progress.)

   The test spectrum for the second gearbox test should be essentially the same as the initial test.

*The power levels indicated for the bench tests refer to transmission ratings. These ratings are not necessarily the same as the engine ratings for the aircraft.

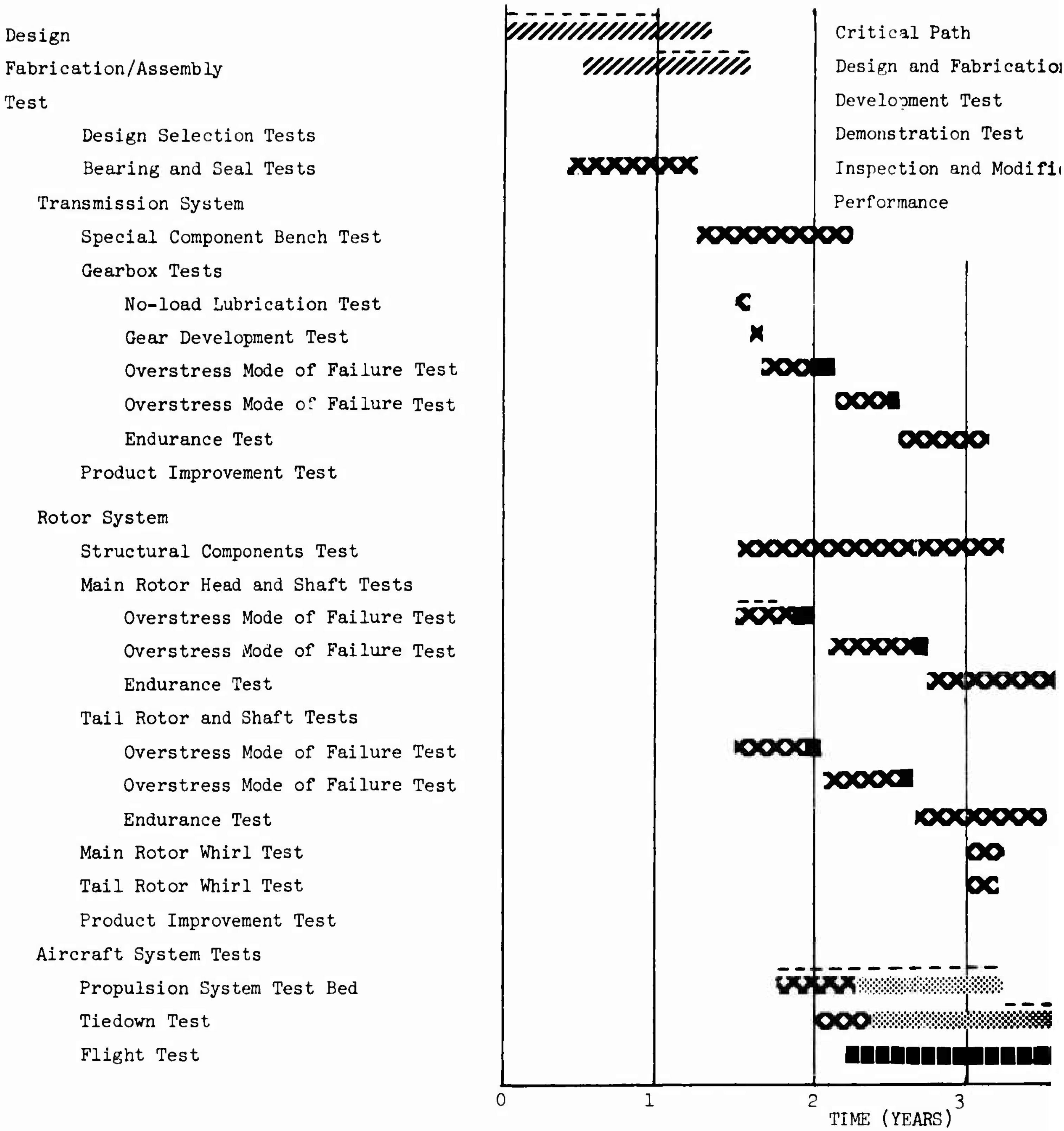
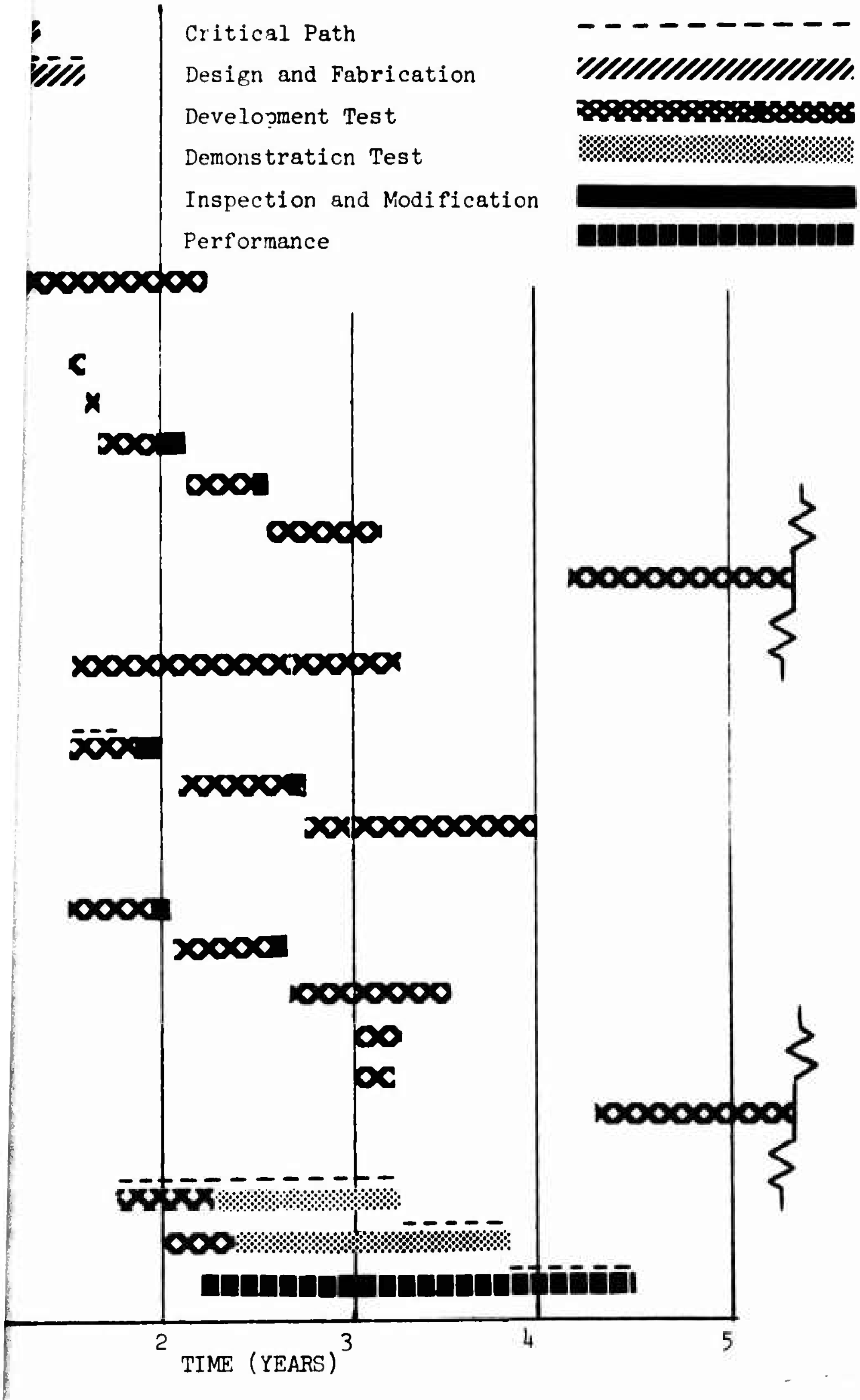


Figure 76. Recommended Test Plan Schedule.


Critical Path
Design and Fabrication
Development Test
Demonstration Test
Inspection and Modification
Performance
2
3
4
5
TIME (YEARS)

3. A 500-hour endurance test with a minimum of 25 percent of the test time at takeoff power with the remaining 75 percent at the most severe mission spectrum with an acceleration factor of 1.25 minimum on all loads, i.e., input shaft, takeoff shafts, and thrusts. The test objective is to demonstrate that the design objectives of reliability are met.

   Many of the component parts of the initial test gearbox could be used for the 500-hour endurance tests. However, new gears, bearings, and the latest designs of improved parts should be installed.

Rotor Head Bench Tests

A minimum of two main rotor head and shaft assemblies should be subjected to the bench tests generally described in the following paragraphs:

1. A 600-hour overstress fatigue test should be performed on the first main rotor head and shaft system in a head and shaft test facility. The percentage of overstress shall be a function of the desired mean strength and test time frame.

   Design modifications should be limited to that hardware which reflects inadequate strength and/or nonfail-safe characteristics.

2. Upon completion of the first fatigue test (defined as all hardware having adequate strength or fail-safe modes, or limiting hardware being defined and modified), the second main rotor and shaft system will then be fatigue tested for 400 hours with required modifications, applying essentially the same test spectra as the initial test.

3. A 500-hour endurance test with approximately a 10-percent acceleration factor is applied to the usage flapping spectrum as the endurance load test spectrum (flapping being the fundamental parameter of a main rotor head and shaft system).

   The edgewise damper load will be accelerated 20 percent, and the blade centrifugal will be accelerated by 10 percent.

   The objectives are to demonstrate that the design objectives of reliability are met and also to reveal problems not always apparent from more highly accelerated tests.

Propulsion System/Tiedown Test

The total propulsion system including all gearboxes, engine(s), rotor heads, blades, shafting, rotor brake, clutches, accessories, and controls should be subjected to the following tests, as a minimum, using either a test bed or the complete tied down helicopter. A test time accumulation of 20 hours should be required prior to first flight of the aircraft and a test time/flight time ratio established at 2/1 for the test program to ensure an adequate test margin of time accumulation on components and system.

Preceding page blank

1. A shakedown test of 50 hours with 50 percent of the test time at takeoff power, 10 percent of the time at 110 percent of takeoff power, and the remaining 40 percent at normal rated power. The test would be divided into five 10-hour cycles with one cycle being at 120 percent of normal rated speed and four cycles at normal speed ranges.

   The objective of this test is to substantiate that the helicopter propulsion system is safe for flight. The requirement is not to pass this test but to substantiate lack of catastrophic failure modes and the fail-safe features of the dynamic components, to satisfactorily substantiate fixes for each mode of failure of major malfunction.

2. A 100-hour endurance test at the same spectrum as the 50-hour shakedown test, consisting of ten 10-hour cycles with two cycles at 120 percent of normal rated speed and 8 cycles at normal speed ranges.

   The objective of this test is to substantiate the adequacy of the modifications developed for earlier problems encountered during the 50-hour shakedown test and flight test and to assure reasonable operating intervals without failures. The requirement is not to "pass" this test, but to obtain a minimum of 50 test hours without failure or major malfunction on all parts scheduled for production.

3. As mentioned in the discussion paragraph, in this recommended test plan an accelerated demonstration test of 2000 hours (800 hours on the propulsion system test bed and 1200 hours on the tiedown test aircraft) would provide the equivalent of a 4000-hour non-accelerated test to demonstrate a component MTBR of 1000 hours at 60-percent confidence with two or less failures exhibited on that component.

Aircraft Flight Test

The helicopter flight test program should be designed to complete the contractors' and contractual aircraft handling qualities, performance, and structural buildup programs in a minimum number of flight hours and in the shortest possible calendar time. In addition to the necessary survey test flights (stress, vibration, etc.),training,and classical procedures of flying at incremental changes in airspeed and center of gravities, a portion of the flight test program should be devoted to flying simulated missions.

Data obtained from these tests can be used to verify the design mission spectrum and to verify the operation and maintainability of the dynamic and airframe components under conditions approaching actual service operation.

Follow-on Product Improvement Tests

Upon completion of the ground test program, including the development and

endurance bench tests and tiedown or dynamic systems tests, a product improvement plan for the propulsion system components should be made. Follow-on bench testing to cover the evaluation of components manufactured by alternate fabrication sources,* additional improvements indicated by field experience, and planned component growth (power capability) should be initiated as soon as possible.

In follow-on programs, a new component incorporating the latest design features should be used. A 200-hour test similar to the overstress development bench tests should be conducted.

The cost curves for this plan can be constructed from the average number of test hours per month in Table XI, the average cost data in Table XII, and the test plan schedule, Figure 70.

SUMMARY

For any helicopter model, the initial and follow-on test programs should be prepared with the objective being to demonstrate that the design requirements for safety, reliability, and maintainability are met.

The essential methods to be employed in the test program to meet this objective are:

1. The use of the multilevel concept and the multiple specimens to account for the variabilities associated with interfaces, strength, manufacturing, and environments.

2. The use of overstress mode-of-failure testing to:

    (a) Uncover modes-of-failure early and to substantiate that they are noncatastrophic and fail-safe by the inspection and detection techniques used in service.

    (b) Verify "fixes" quickly.

3. The conduction of accelerated demonstration testing to reasonably verify that the design objectives are met.

4. The establishment of logical test scheduling such that there is probability that the components will be free of major problems before entering subsequent, higher levels of testing with the ultimate goal of effectively demonstrating that the design requirements for reliability and maintainability have been achieved by the time the aircraft are deployed.

*Some evaluation of alternate sources can be accomplished (if sources are available) in the second development or endurance test.

COMMENTS ON APPLICABLE MILITARY SPECIFICATIONS

In accordance with contract requirements, those Military specifications which are applicable to helicopter dynamic components have been reviewed in relation to this study, and comments on these specifications are listed below:

MIL-A-8064B (USAF); ACTUATORS AND ACTUATING SYSTEMS, AIRCRAFT, ELECTRO-MECHANICAL, GENERAL REQUIREMENTS FOR

This specification references MIL-STD-810, which concerns environmental testing. Neither of these specifications requires the actuators to be operated during the environmental testing. Meaningful testing requires close simulation with service experience and as such, the actuators should be operated during environmental testing.

MIL-C-5503C; CYLINDERS: AERONAUTICAL, HYDRAULIC ACTUATING GENERAL REQUIREMENTS FOR

The extreme temperature test requirement that "O" rings and seals must withstand, 275° centigrade, should be reexamined since "O" rings cannot withstand this temperature and remain in acceptable condition for further service.

MIL-D-23222; DEMONSTRATION REQUIREMENTS FOR ROTARY WING AIRCRAFT

Regarding drive train demonstration requirements, no significant technical changes are recommended. Using procedures outlined in the specification addenda, it is now possible to make normal modifications to suit specific needs whenever necessary.

MIL-T-5955C; TRANSMISSION SYSTEMS, VTOL - STOL, GENERAL REQUIREMENTS FOR

This specification outlines the general requirements for V/STOL transmission systems. The specification makes reference to "as specified in the aircraft detail specification" and as such, several items are tailored to individual requirements. Thus, the detail specification is the governing factor for several important requirements. The requirement of paragraph 4.3.1 for variable speed capability will increase the cost and complexity of test stands.

Development tests are still not included, even in the latest revision. Any future helicopter program should include such tests, but under present specifications, these will be prepared by the contractor and approved by the procuring activity.

MIL-T-8679; TEST REQUIREMENTS, GROUND, HELICOPTER

Paragraph 3.6.2 requires 450 hours of tiedown testing: a 50-hour preliminary flight-approved test, a 150-hour preproduction test, and a 250-hour ground test. The first two are mandatory, while the third test is at the option of the procuring activity. Since the majority of the malfunctions

are experienced during the early phases of the test program, the total 450-hour requirement could be reduced to 250 hours, in 50-, 100-, and 100-hour increments. More effective rotor and transmission system testing is conducted in system tests on the head and shaft tester and in the regenerative test stands. The reduced time suggested here is still sufficient for resolving installation problem areas.

Provision should also be included for using a propulsion system test bed during development and qualification testing. The propulsion system test bed has been an effective tool in developing complete dynamic systems prior to developing and without requiring airframe hardware. Some of this testing should be development testing without "must-pass" requirements.

MIL-H-8775C; HYDRAULIC SYSTEM COMPONENTS, AIRCRAFT AND MISSILES

Paragraph 4.5.6 concerns extreme temperature testing. This requirement should be reexamined since "O" rings cannot withstand 275° centigrade and remain in acceptable condition for further service.

Paragraph 4.5.9 concerns vibration, and reference is made to MIL-E-5272 which is tailored to electronics equipment and does not lend itself to hydraulic components. As such, the test conditions are not representative of conditions experienced in service.

CONCLUSIONS

1. Future helicopter programs should include a comprehensive test plan consisting of three separate and distinct phases:

    a. Development type testing, including subcomponent testing, should be conducted to provide early problem definition and thereby allow component modification if required, before components are in large scale production. Such tests should not have definite acceptance and rejection criteria.

    b. Qualification testing may be required by the procuring activity. This testing should supplement the development testing and should be conducted similar to present procedures with definite reliability performance requirements.

    c. Production improvement programs for dynamic components should be included in the original contract or negotiated during the initial prototype program. These tests will permit development of the hardware and provide growth potential during the aircraft program.

2. The preceding tests should include environmental testing that simulates that to be expected during operation. Individual detail specifications for each type helicopter should include a usage spectrum at the various environments.

3. The practice of assigning TBO intervals based on limited testing should be carefully reassessed. Service intervals for dynamic components should approach "on-condition" operation. Low service intervals contribute to increased maintenance and do not necessarily assure safe operation. The use of failure rate analysis programs can determine the economic feasibility of approaching "on-condition" operation.

4. A standardized reporting system should be developed and used by all military services to report service malfunction and removal data. This system should be specified during the initial phases of a contract and maintained for a prescribed time interval to allow operational performance to be assessed correctly.

APPENDIX I

SUPPLEMENTARY DATA TO TEST PROGRAM TRADE-OFF STUDIES

TEST PLAN DEVELOPMENT

In the development of the test plan used in the trade-off studies of component realiability demonstration, four test plans were considered. The organization, flow, and bar charts for the three additional test plans, described below, are included on the following pages.

Plan 1

Plan is included in the section entitled "Test Program Trade-Off Studies".

Plan 2

This plan, which was the baseline from which all four test plans were developed, is essentially extracted from the original test program used for the H-3. In this plan, no attempt has been made to introduce tests that will uncover in development or qualification any of the problems that were uncovered after the H-3 went into service. Figures 77, 78, and 79 define this test program in detail.

Plan 3

The third plan represents the approach of "tacking-on" test conditions or additional tests to Plan 2. This approach is frequently used when existing facilities or test plans are to be employed for different purposes. In this plan, tests have been added to detect some of the service modes of failures not detected in Plan 2. Figures 80, 81, and 82 described this program.

Plan 4

The fourth plan, Figures 83, 84, and 85, is derived from the program used in the trade-off study. The approach in this plan is to eliminate all but the most important tests or test conditions in the plan studied. The most important tests are those that qualify the flight critical components (fatigue tests) and those that reveal the major service problems not uncovered in the H-3 test program (Plan 2).

Number of Components Required

The number of components required to implement plans 2,3, and 4 and to demonstrate a MTBR of 500 hours at a confidence level of 60 percent are shown in Table XVI. The test plan (Plan 1) used for the trade-off study is included for comparative purposes.

Reliability Prediction

The confidence placed with each test plan in predicting the various modes

of component failure is shown in Table XVII. Included herein are all four test plans. The definition of reliability for these various failure modes is shown in Table XVIII.

TABLE XVI. COMPONENT REQUIREMENTS FOR THE FOUR TEST PLANS

Component	Test Plan 1	2	3	4
Main Rotor Head(1)	1 PP 4 P	6 P	5 P	4 P
Main Rotor Blade	4 PP 18 P	24 P	24 P	18 P
Tail Rotor Head(1)	1 PP 4 P	6 P	5 P	4 P
Tail Rotor Blade	4 PP 16 P	24 P	20 P	16 P
Main Gearbox	1 PP 8 P(2)	9 P(2)	9 P(2)	7 P(2)
Intermediate Gearbox	1 PP 8 P(2)	9 P(2)	9 P(2)	7 P(2)
Tail Gearbox	1 PP 8 P(2)	9 P(2)	9 P(2)	7 P(2)
Subassembly of Rotor or Transmission System Component	10 M 3 PP 4 P	12 P	11 P	8 P
Engines	3 P	3 P	3 P	3 P
Complete Aircraft	1 P(3)	1 P(3)	1 P(3)	0

M = Model Parts
PP = Production Prototype Parts
P = Production Parts

(1) Does not include blades

(2) Includes slave transmission to complete regenerative loop.

(3) Flight aircraft not included.

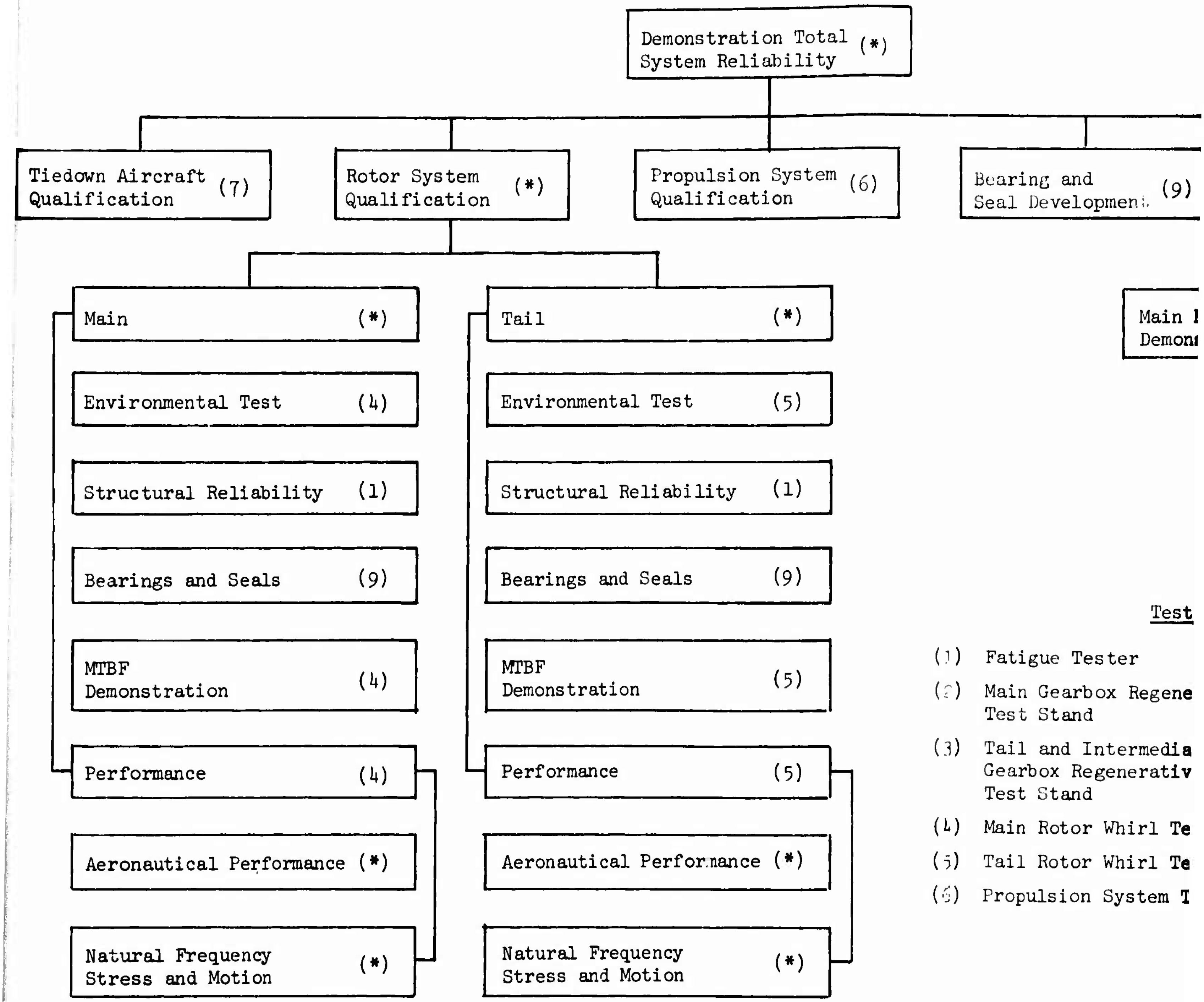
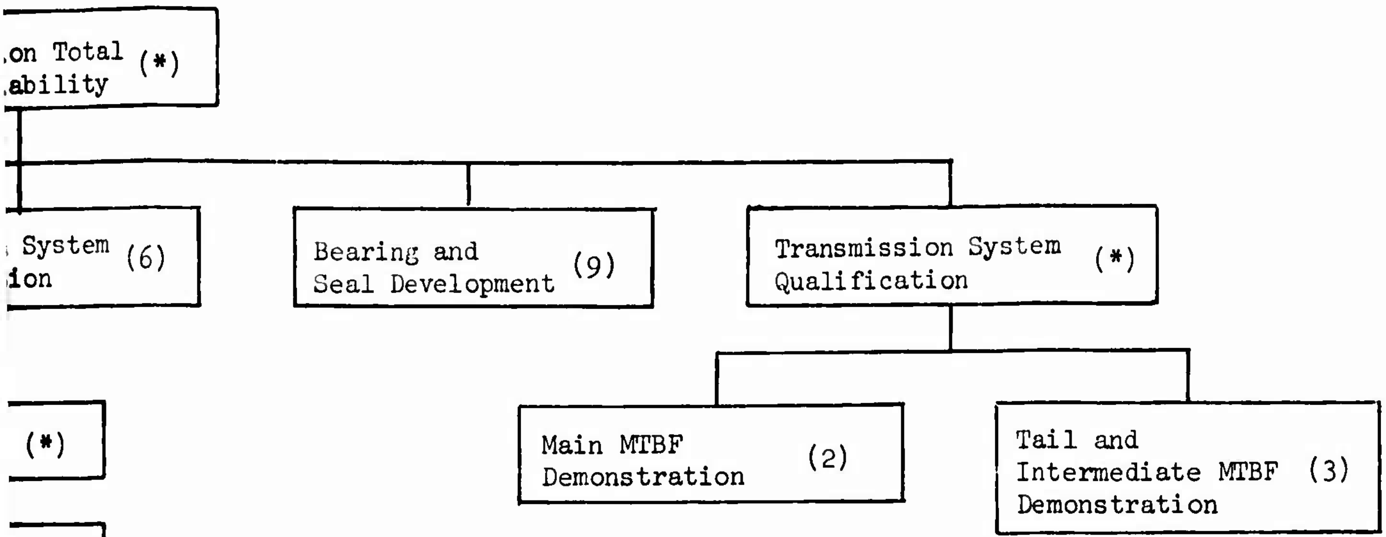
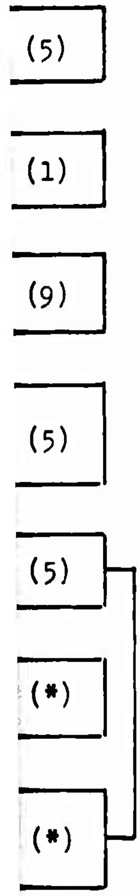


Figure 77. Plan 2, Test Plan.





<u>Test Facility Legend</u>

(1) Fatigue Tester

(2) Main Gearbox Regenerative Test Stand

(3) Tail and Intermediate Gearbox Regenerative Test Stand

(4) Main Rotor Whirl Test Stand

(5) Tail Rotor Whirl Test Stand

(6) Propulsion System Test Bed

(7) Tiedown Aircraft

(8) Flight Aircraft

(9) Small-Scale Development Test Equipment

(10) Main Rotor Head and Shaft Tester

(11) Tail Rotor Head and Shaft Tester

(*) The facility number(s) is (are) the same as the one(s) for the adjacent block(s) tying into it.

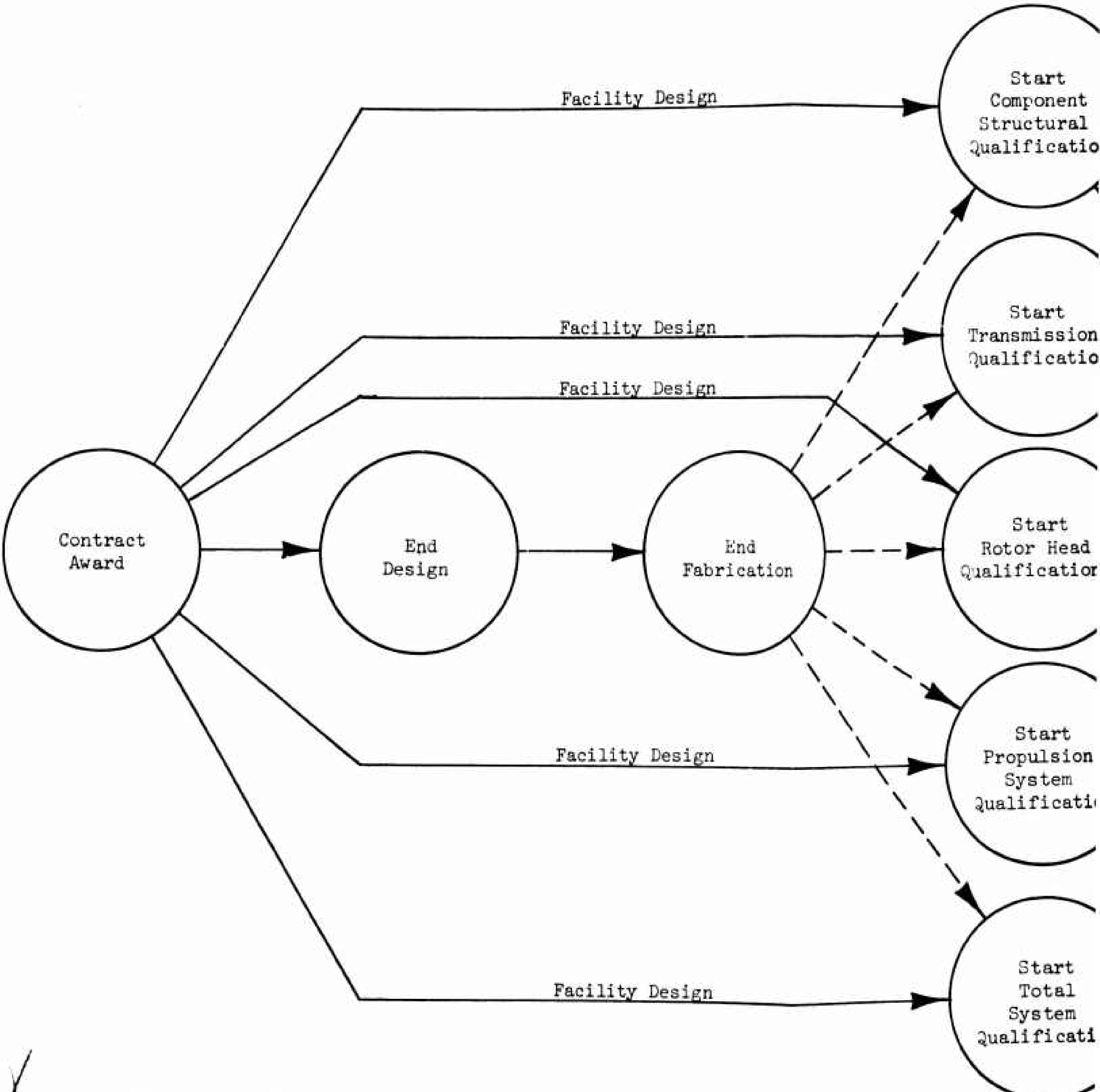
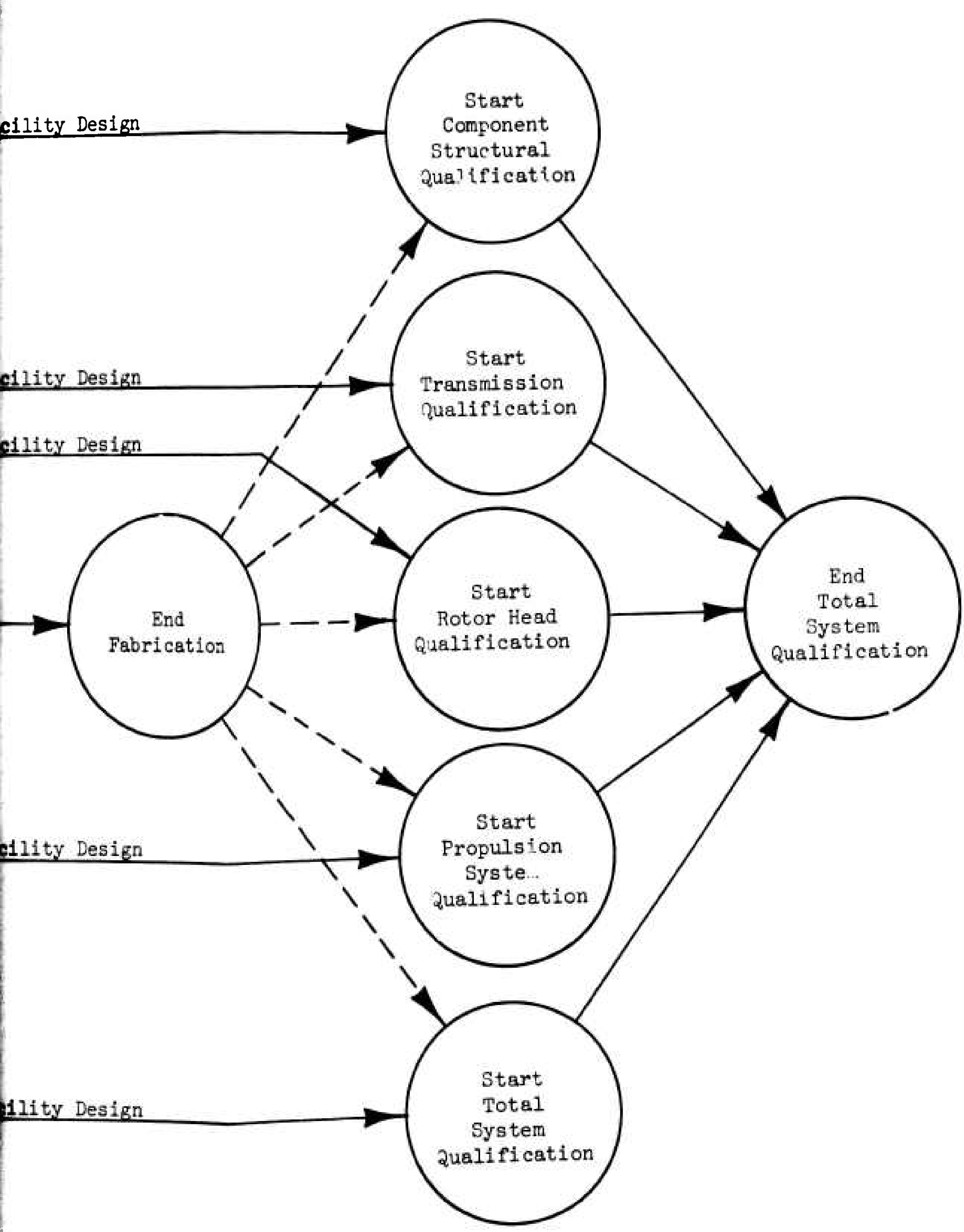


Figure 78. Plan 2, Flow Chart.

Preceding page blank


cility Design
Start
Component
Structural
Qualification
cility Design
Start
Transmission
Qualification
cility Design
End
Fabrication
Start
Rotor Head
Qualification
End
Total
System
Qualification
cility Design
Start
Propulsion
System
Qualification
ility Design
Start
Total
System
Qualification

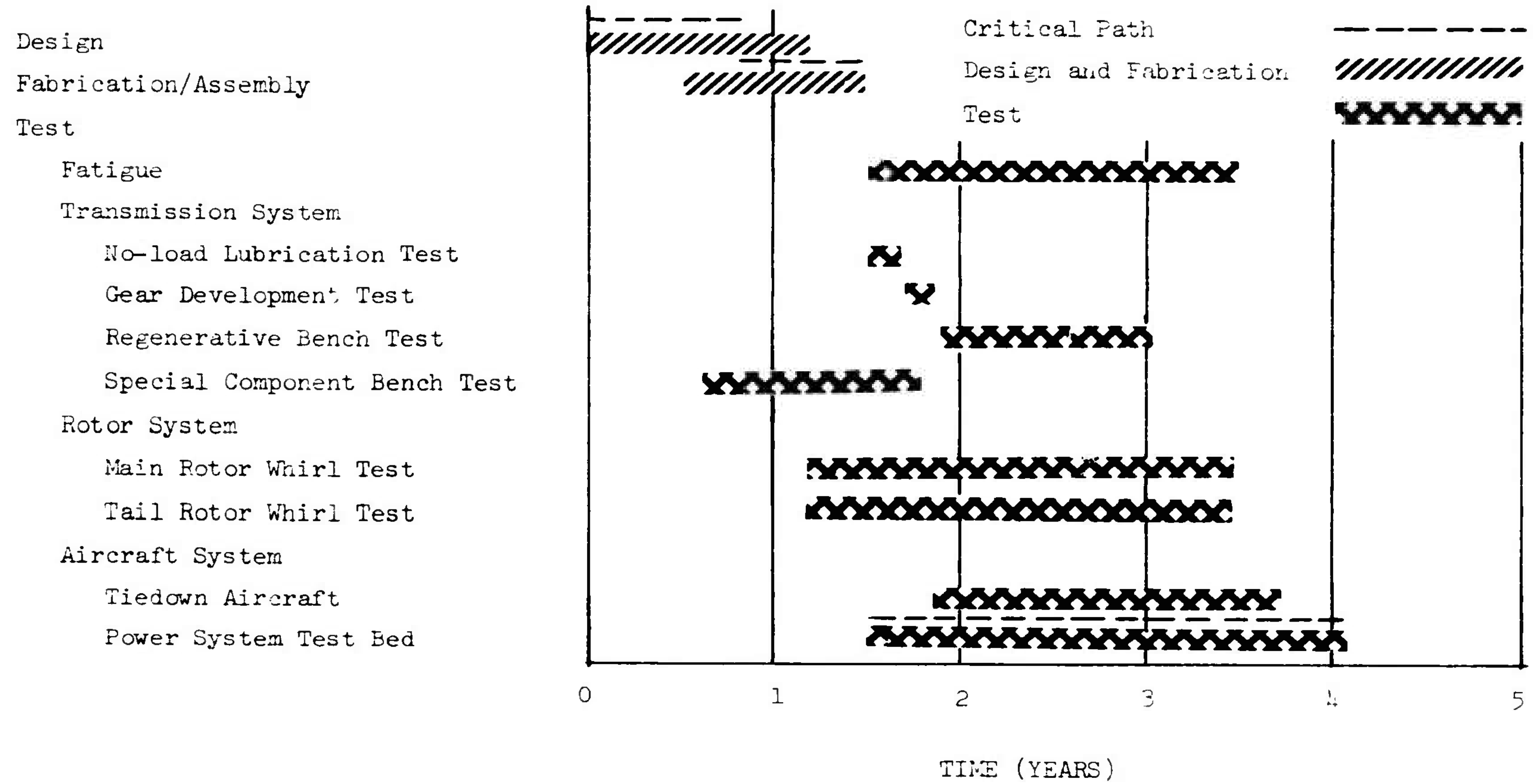


Figure 79. Plan 2. Concurrent Schedule.

Preceding page blank

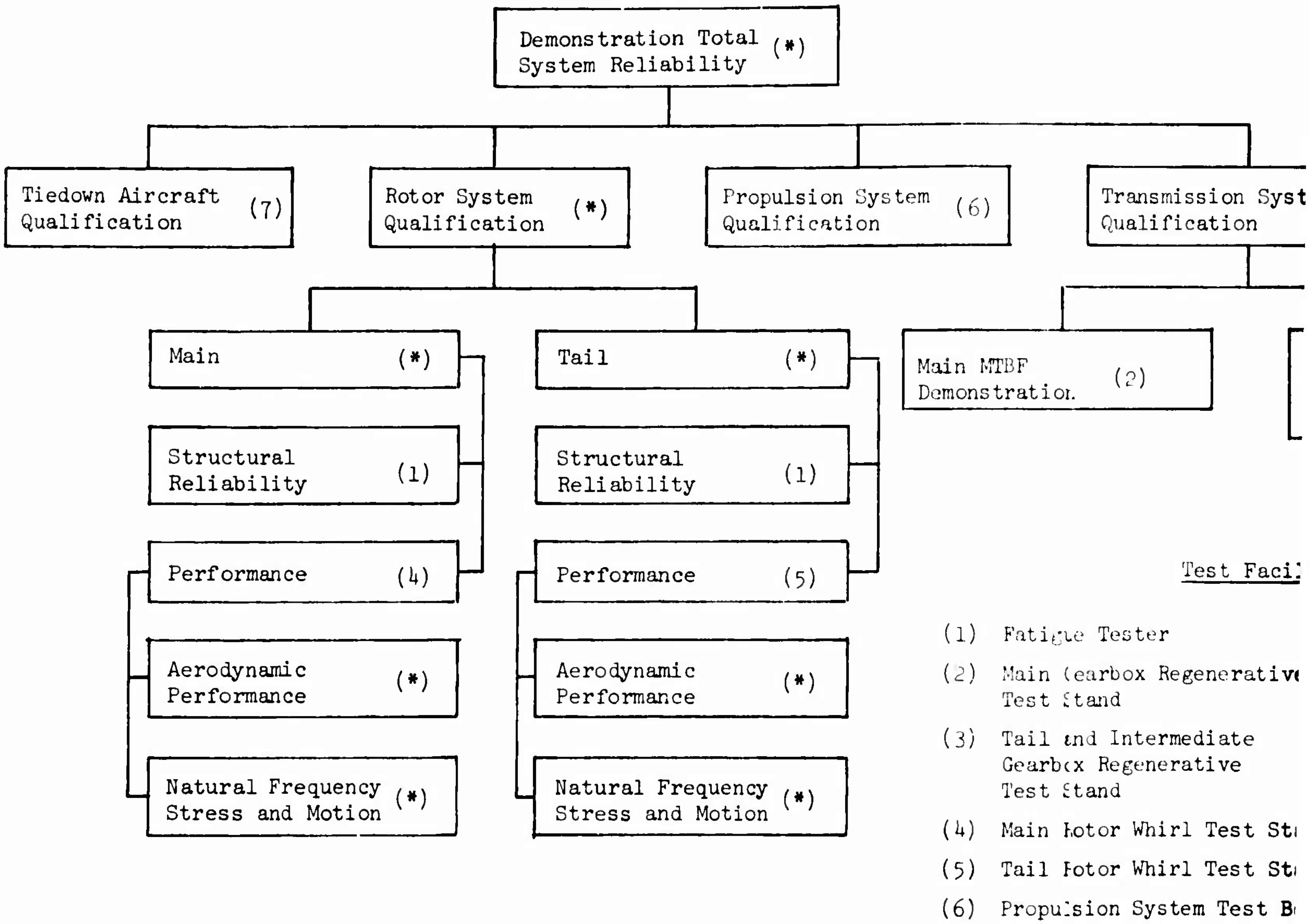
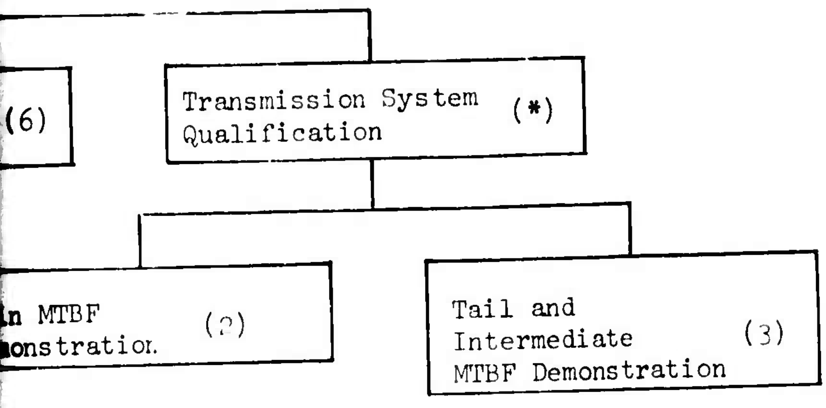


Figure 80. Plan 3, Test Plan.



Test Facility Legend

(1) Fatigue Tester

(2) Main Gearbox Regenerative Test Stand

(3) Tail and Intermediate Gearbox Regenerative Test Stand

(4) Main Rotor Whirl Test Stand

(5) Tail Rotor Whirl Test Stand

(6) Propulsion System Test Bed

(7) Tiedown Aircraft

(8) Flight Aircraft

(9) Small-Scale Development Test Equipment

(10) Main Rotor Head and Shaft Tester

(11) Tail Rotor Head and Shaft Tester

(*) The facility number(s) is (are) the same as the one(s) for the adjacent block(s) tying into it.

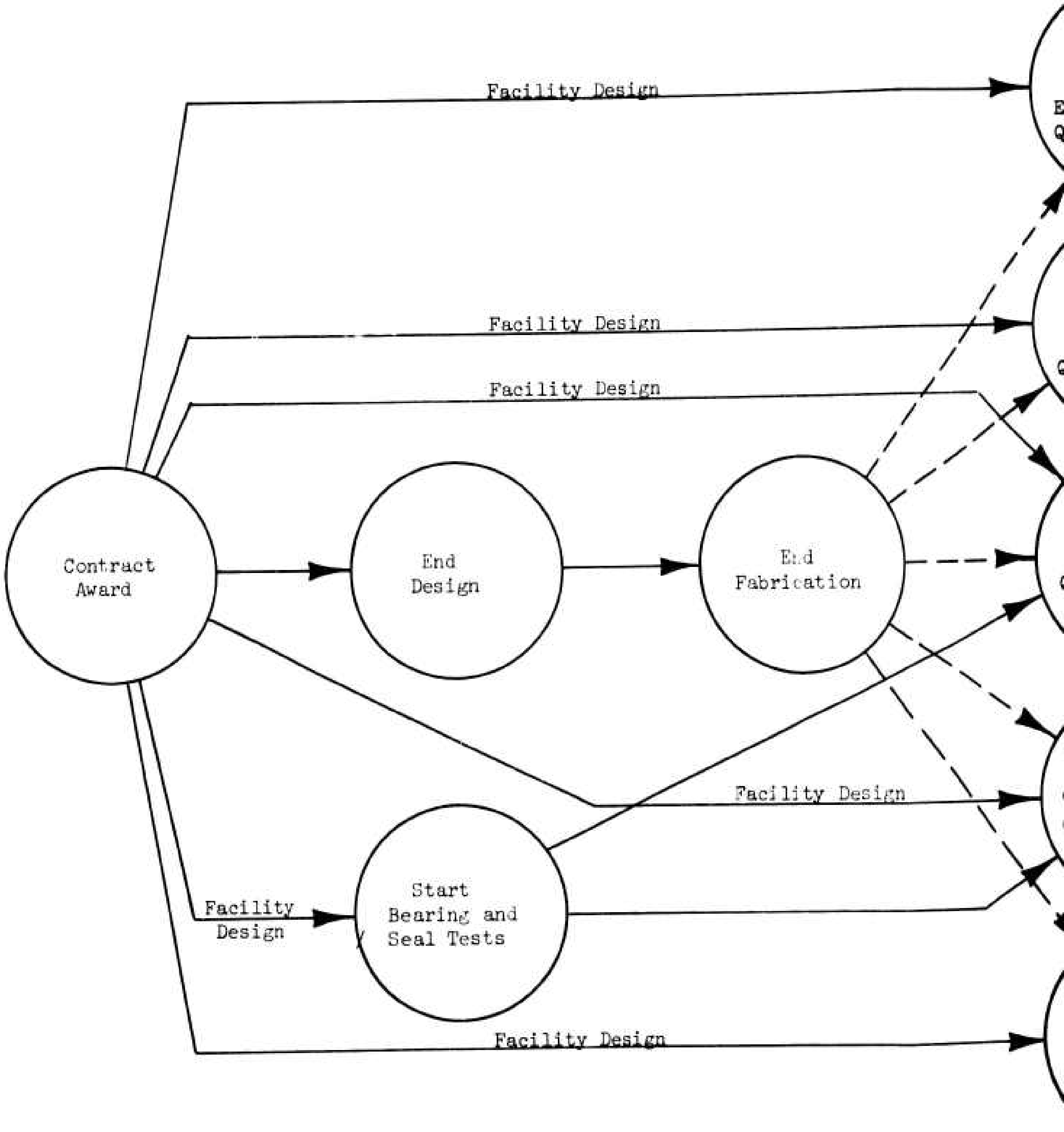
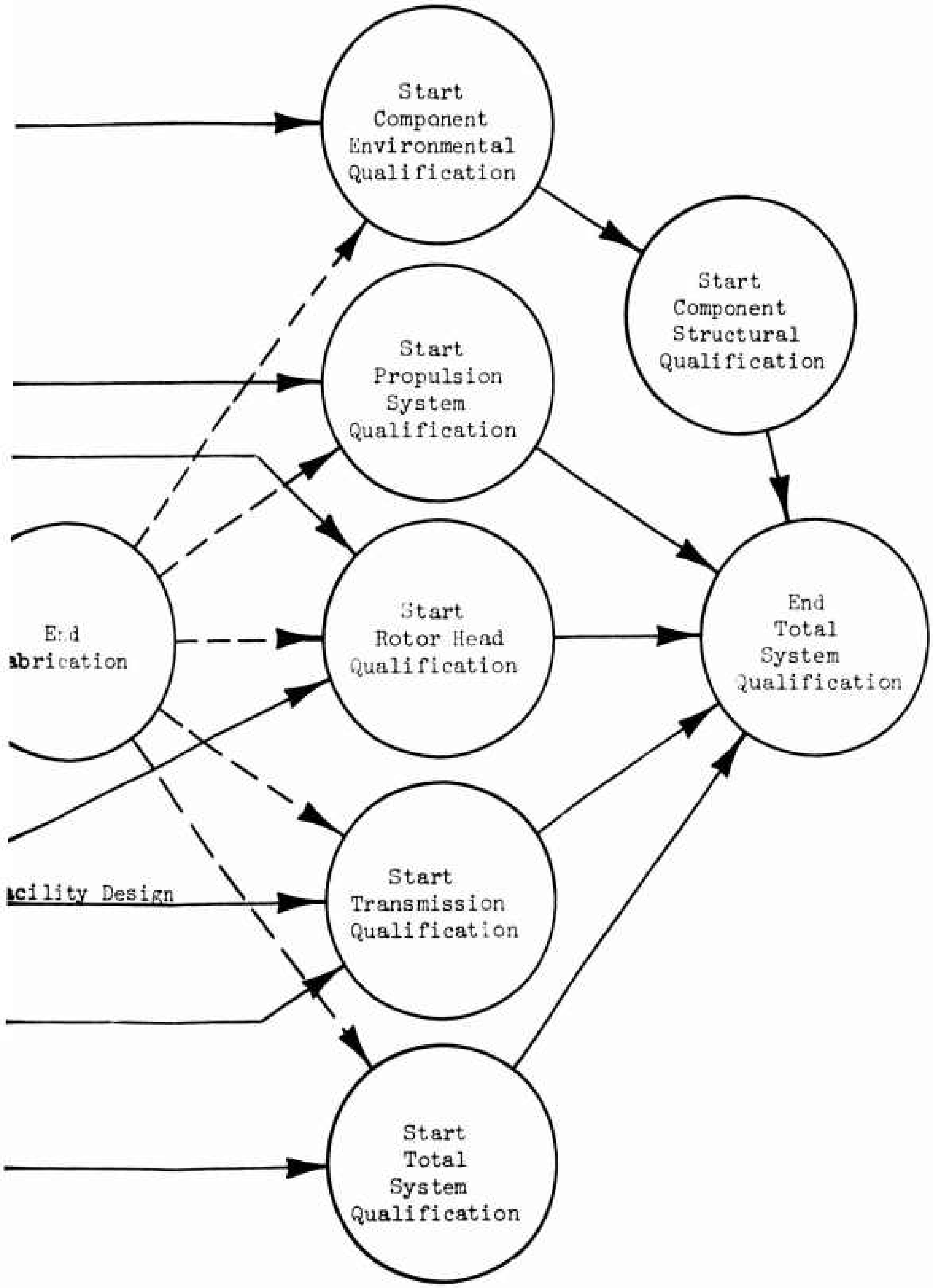


Figure 81. Plan 3, Flow Chart.

Preceding page blank



Start Component Environmental Qualification
Start Component Structural Qualification
Start Propulsion System Qualification
End abrication
Start Rotor Head Qualification
End Total System Qualification
acility Design
Start Transmission Qualification
Start Total System Qualification

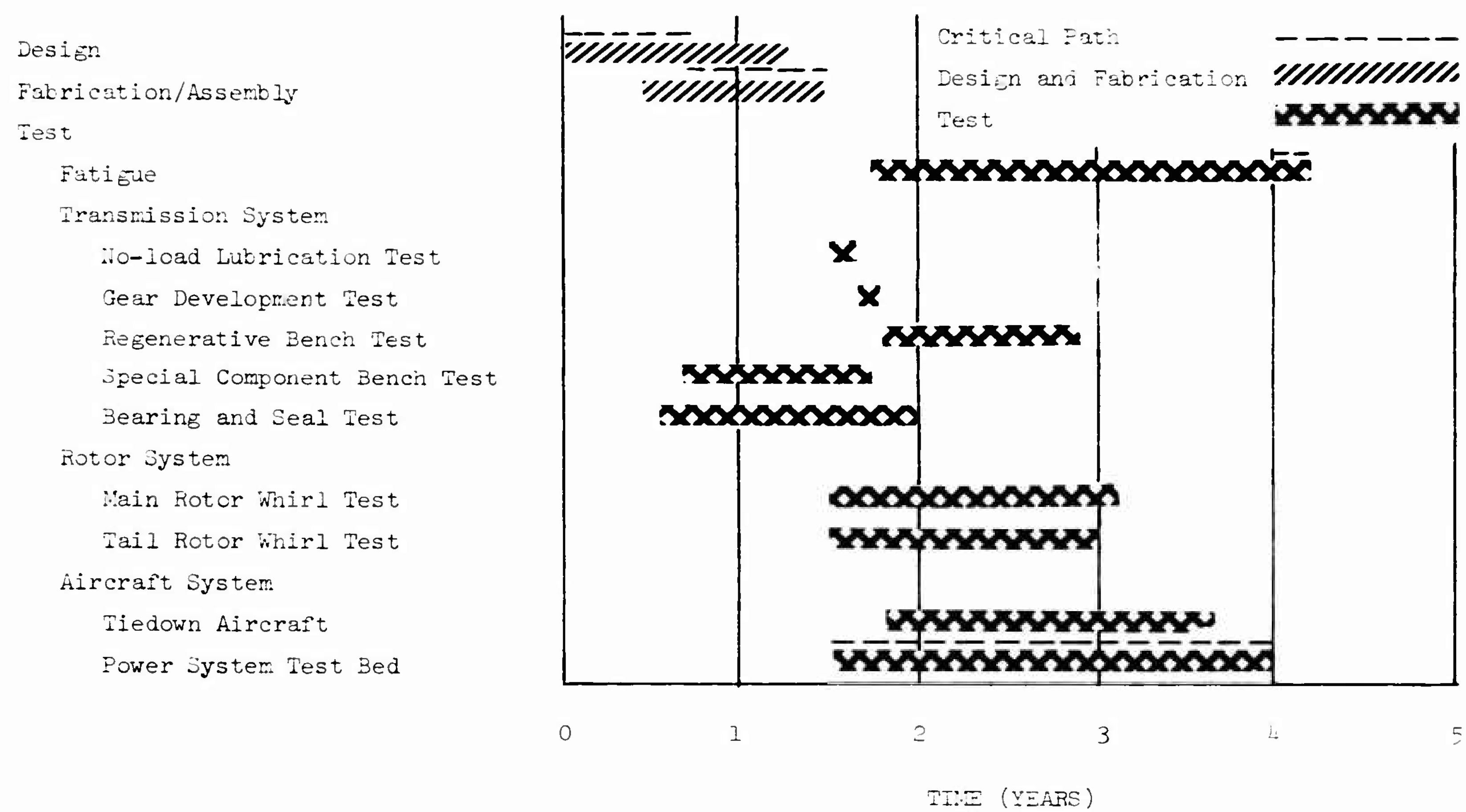
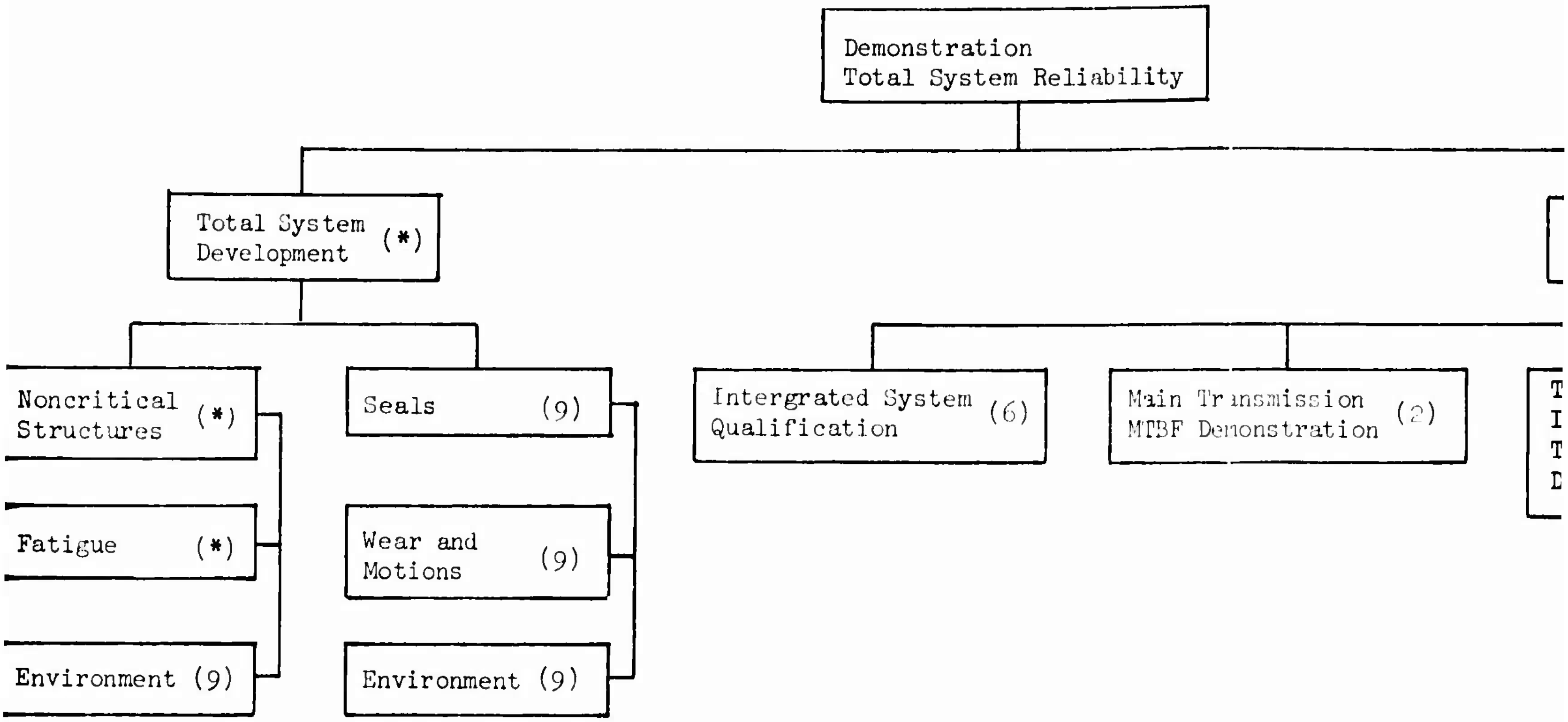


Figure 82. Plan 3, Concurrent Schedule.

Preceding page blank



(1) Fatigue Tester

(2) Main Gearbox Regenerative Test Stand

(3) Tail and Intermediate Gearbox Regenerative Test Stand

(4) Main Rotor Whirl Test Stand

(5) Tail Rotor Whirl Test Stand

(6) Propulsion System Test Bed

(7) Tiedown Aircraft

(8) Flight Aircraft

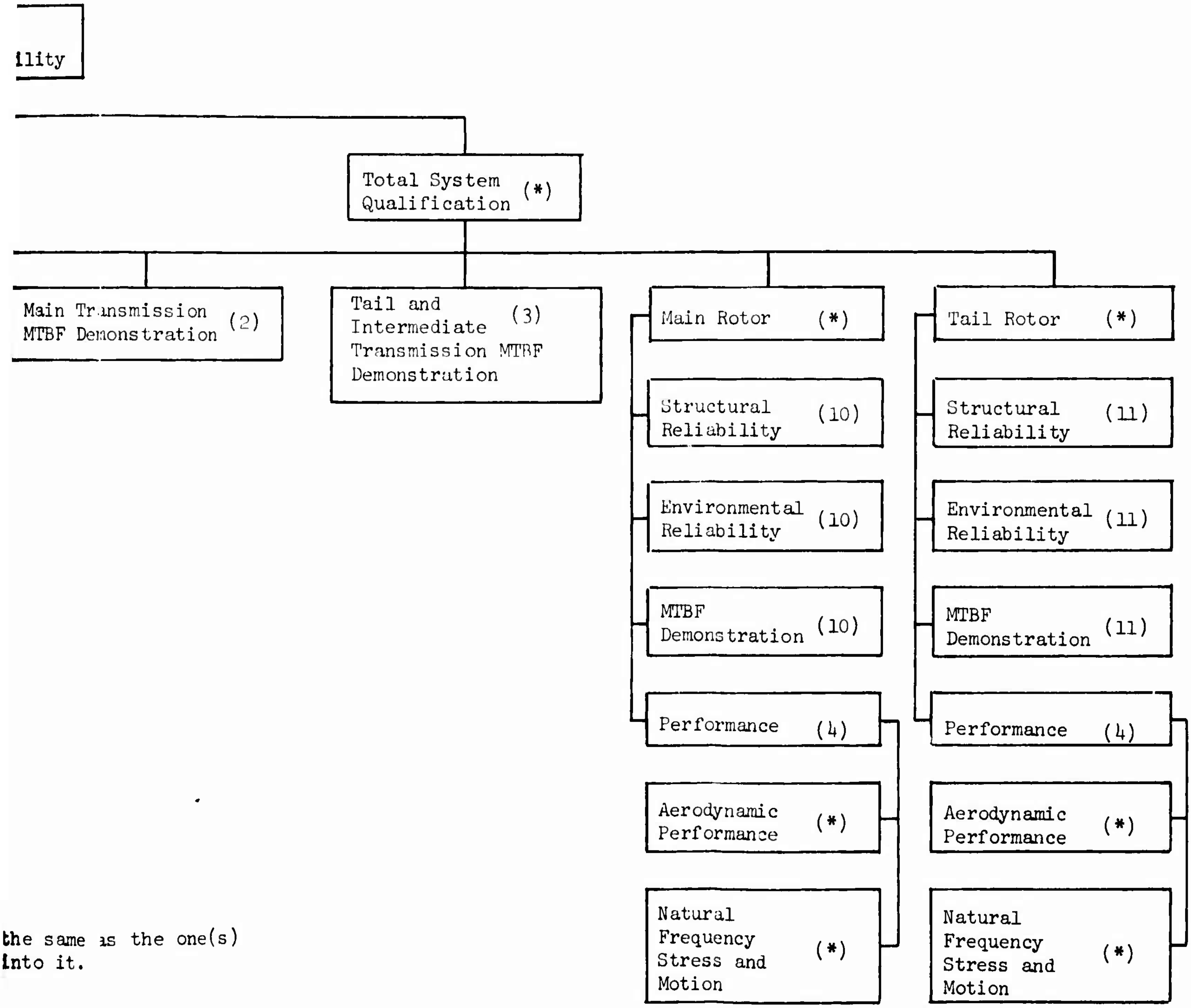
(9) Small-Scale Development Test Equipment

(10) Main Rotor Head and Shaft Tester

(11) Tail Rotor Head and Shaft Tester

(*) The facility number(s) is (are) the same as the one(s) for the adjacent block(s) tying into it.

Figure 83. Plan 4, Test Plan.



the same as the one(s)
into it.

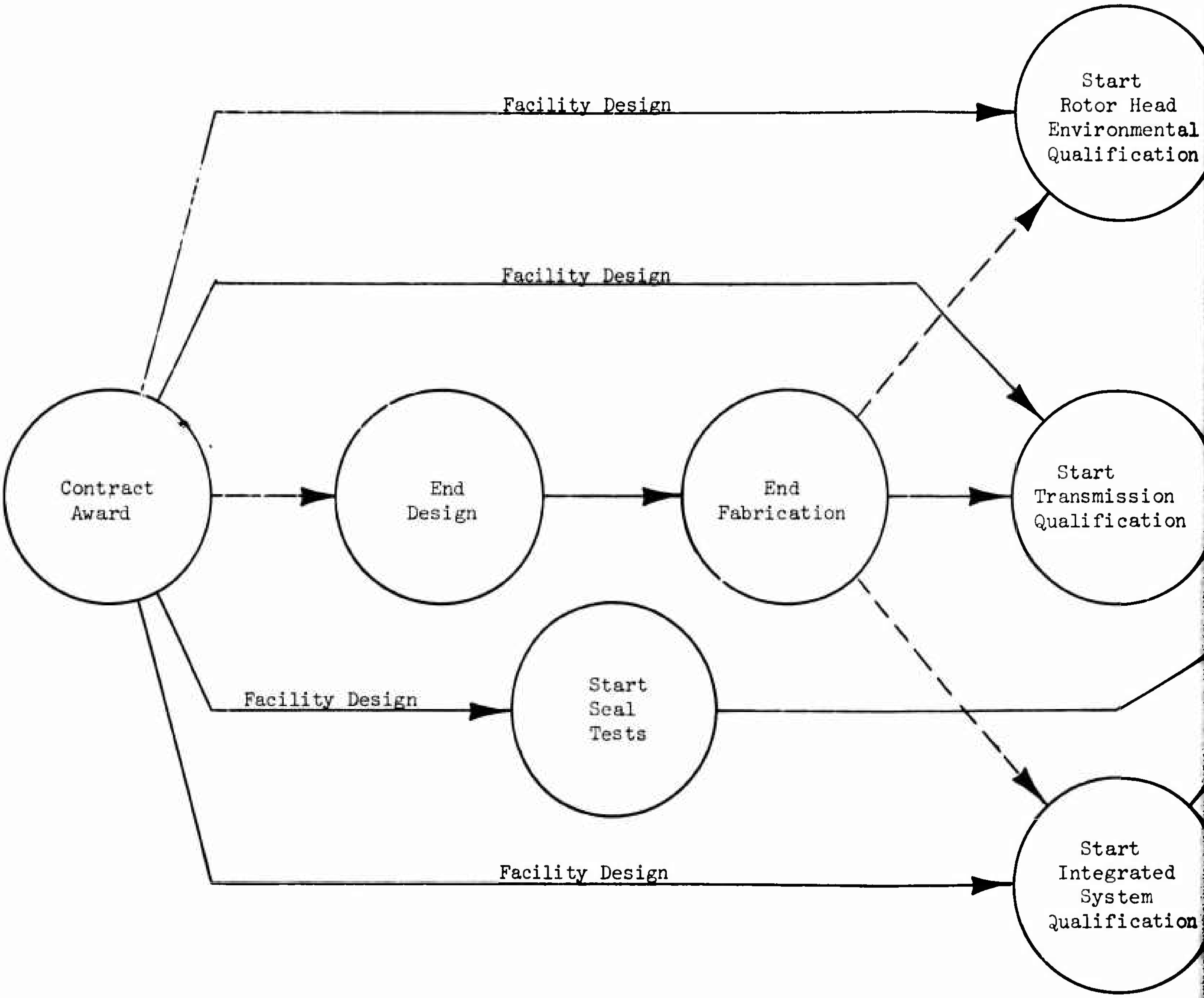
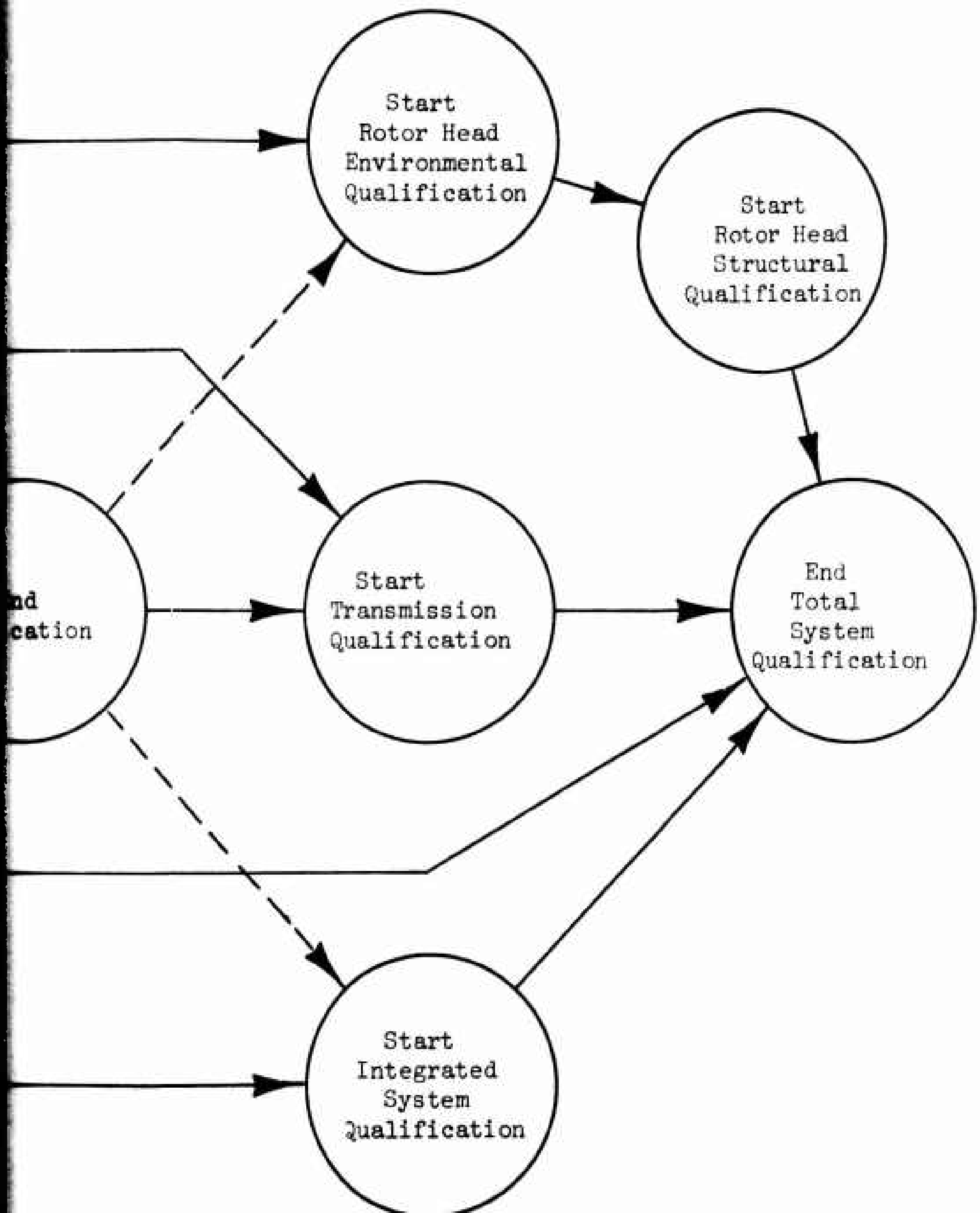


Figure 84. Plan 4, Flow Chart

Preceding page blank



Start
Rotor Head
Environmental
Qualification
Start
Rotor Head
Structural
Qualification
nd
cation
Start
Transmission
Qualification
End
Total
System
Qualification
Start
Integrated
System
Qualification

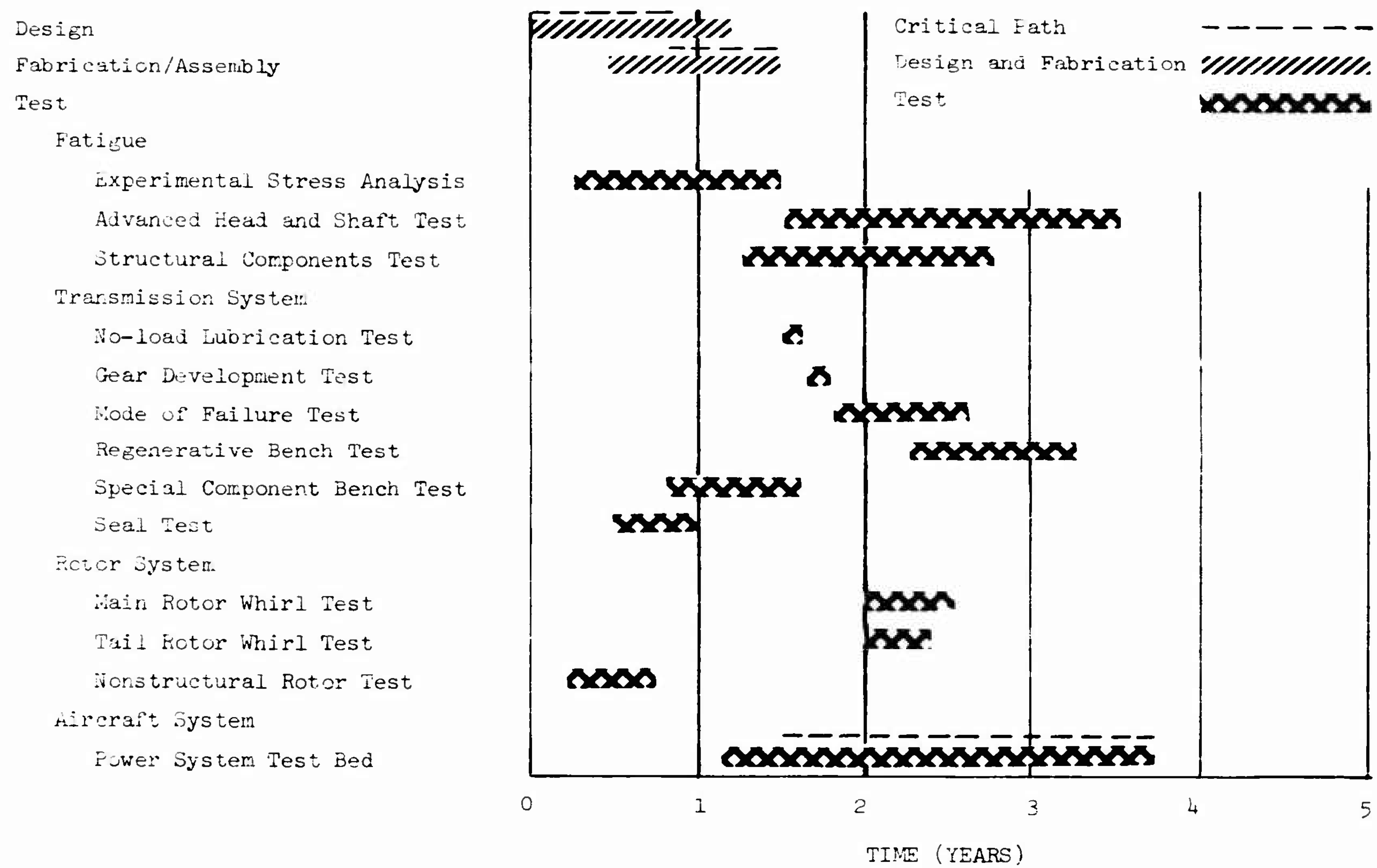


Figure 85. Plan 4, Concurrent Schedule.

TABLE XVII. RELIABILITY PREDICTIONS USING THE FOUR TEST PLANS

Type of Failure	Test Plan 1	2	3	4
Seal Failures - Functional	3*	1	3*	3*
Seal Failures - Environmental	2*	0	2*	2*
Bearing Failures - Functional	3*	1*	3*	1*
Bearing Failures - Environmental	2*	0	2*	1*
Abrasion Strips	2*	0	0	1*
Gear Failures	2*	1*	1*	1*
Nonstructural Fatigue Failures	1*	0	0	1*
Miscellaneous Environmental	0	0	0	0
Failures caused by lack of lubricant	1	1	1	1
Structural Failures of Rotor Head and Flight Critical Systems	3*	1*	1*	2*
Structural Transmission Excluding Gears	2*	1	1	1

0 - Reliability problem cannot be identified.

1 - Reliability problem can be identified during qualification phase only.

2 - Reliability problem can be identified during development phase before qualification phase.

3 - Reliability problem can be identified before final design.

* - Reliability problem can be quantified.

TABLE XVIII. RELIABILITY DEFINITIONS USING THE FOUR TEST PLANS

Plan Number	Extent of Reliability Program Identified	Degree to Which Actual Reliability Values may be Determined	Hypothesis of Acceptance Criteria	Compatibility with Overall Development Criteria
2	Seal Failures	Due to infrequent nature of these failures, an estimate of MTBF may be assigned with little confidence.	Based upon visual or measured assessment, "excessive leakage" dependent upon particular application.	Lack of quantification renders this of no use in determining system reliability quantitatively. There are some instances, however, where seals limited the system reliability
1 and 3	Seal Failures and Environmental Seal Failures	The increased number of seal failures under total environmental conditions and total load and displacement conditions allows an estimate of MTBF with greater confidence than with Plan 2.	Based on visual or measured leakage, wear or failure dependent upon particular application.	Completely compatible with even the most statistical analysis because of the larger population on which the reliability value is based.
4	Seal Failures and Environmental Seal Failures	Same as above with the exception that only a limited environmental spectrum is applied.	Same as above	Same as above

TABLE XVIII - Continued

Plan Number	Extent of Reliability Program Identified	Degree to which Actual Reliability Values may be Determined	Hypothesis of Acceptance Criteria	Compatibility with Overall Development Criteria
2 and 4	Rotor Head and Transmission Bearing Failures and Gear Failures	Failures in these areas are frequent enough to obtain an estimate of MTBF with reasonable confidence. Estimates are reduced to normal loads from accelerated levels by using well-established procedures.	Based upon visual appearance or manual "feel" in the case of bearings. In the case of gears and some bearings, this is based on absence of a fatigue crack or failure.	Completely compatible
4	Environmental Bearing Failures	Pertains mainly to rotor head bearings. Failures are sufficient in number to produce a good estimate of MTBF for any selected installation.	Same as above	Same as above
1 and 3	Bearing Structural and Environmental Failures and Gear Failures	Because these are run on a prototype basis, sufficient failures are available to obtain an estimate of MTBF for a particular installation. The possibility exists of advancing the state of the art in these tests and also of applying the methodology of structural component fatigue failures to gears.	Same as above	Same as above

TABLE XVIII - Continued

Plan Number	Extent of Reliability Program Identified	Degree to which Actual Reliability Values may be Determined	Hypothesis of Acceptance Criteria	Compatibility with Overall Development Criteria
1 and 4	Abrasion Strips and Nonstructural Fatigue (tipcaps, pockets, fairings)	Same as above	Abrasion strips: based on acceptable wear rate and structural integrity. Non-structural fatigue: based upon fatigue life calculated in accordance with structural fatigue methodology.	Same as above
1 2 3 and 4	Lack of Lubricant	None	Temperature within acceptable limits with no evidence of component failure.	None, cannot quantify
2 3 and 4	Structural Rotor Head	The procedure involves the use of Miner's cumulative damage theorem. Test data is used to construct S/N curves, and by the use of flight data and the above theorem, a replacement time is calculated. This operation uses an S/N curve reduced by three standard deviations from the S/N curve based on test data. Therefore there is in every	(a) Demonstration of fail-safe design based on: multiple load paths, early warning system, long crack propagation times. (b) Fatigue failure at a load level and number of cycles that produce a calculated replacement time several orders of magnitude above the reliability	Compatibility is complete; however, MTBF is determined differently for transmission or rotor head assemblies. The criteria to the left are far more stringent than any required for a total system.

TABLE XVIII - Continued

Plan Number	Extent of Reliability Program Identified	Degree to which Actual Reliability Values may be Determined	Hypothesis of Acceptance Criteria	Compatibility with Overall Development Criteria
2 3 and 4	Structural Rotor Head	statement of life a very conservative reduction. In addition, mode of failure, failure warning systems, and crack propagation data obtained during test serve to further establish the fail-safe nature of the part under consideration.	requirements for the system.	
		The environmental aspects of the tests would be handled on an hour-to-hour basis where no rational acceleration technique was available.	(c) Wearout caused by an equivalent number of flight hours above the required MTBR.	
1	Structural Rotor Head	Same as above except that model tests produce these results much earlier	Same as above but including poor stress patterns as structural failure criteria.	Same as above

TABLE XVIII - Continued

Plan Number	Extent of Reliability Program Identified	Degree to which Actual Reliability Values may be Determined	Hypothesis of Acceptance Criteria	Compatibility with Overall Development Criteria
2 3 and 4	Structural Transmission Gear (includes shafts, housings, lugs, etc.)	Failures are too infrequent to provide for more than an estimate of MTBF, excluding gearing.	Fatigue failure	It adds nothing
1	Same as above	Failures are sufficiently frequent to apply fatigue methodology and obtain a meaningful estimate of MTBF.	Same as above	Complete

APPENDIX II

THE FAILURE RATE ANALYSIS PROGRAM

INTRODUCTION

Two primary factors that must be considered in establishing a TBO are safety and economics. Safety is of utmost importance since the established TBO cannot cause an unacceptable probability that a catastrophic mode of failure will occur. There must be a thorough understanding of the potential catastrophic modes of failure. Redundancies and detection systems should be used where practical. Testing must identify components with limited service intervals, and retirement of those parts must be considered in the TBO program. In addition, the established TBO must be economically sound. In order to make a decision as to the economic soundness of a given TBO, the failure rate variation with time must be understood. Sikorsky Aircraft has developed an analytical tool which allows determination of the variation of the failure rate versus time for a given component, recognition of the predominant modes of failure (and how each affects the failure rate behavior of the total component), and determination of the probability that a component will survive to any given time (and the variation of that probability if any given mode of failure is corrected).

The analytical tool developed for this purpose is known as the Failure Rate Analysis Program (FRAP). The basic principles of this program were used in a similar program in a study of the SH-3A main gearbox.(*) The following pages discuss the use and capabilities of FRAP and demonstrate its use for the analysis of the CH-3C/HH-3E intermediate and tail gearboxes and main and tail rotor heads.

USE AND CAPABILITIES OF FRAP

FRAP uses major component removal histories (failures, high time removals, and other removals); sorts and edits these histories to identify missing or faulty data; prints out a plot of failures versus the time since overhaul (TSO) where the time since overhaul is a nonlinear scale; applies a Kolmogorov-Smirnov statistical test to the plot to determine (to a given confidence level) if the failure rate is nonconstant; identifies predominant modes of failure and their effects upon the failure rate behavior; and plots the probability of survival to any given time since overhaul for any given combination of modes of failure, up to the highest operating life.

Component removal histories require the following data:

(1) Component identification (P/N, S/N).

(2) Aircraft from which removed and total time on aircraft.

(3) Date of removal.

(4) Whether removal was due to failure, high time or other causes.

(*) SER-50547 Study of Helicopter Transmission System Development Testing Dated June 5, 1968.

(5) Total time accumulated on component and time since last overhaul.

(6) Where removal was due to failure, the part responsible for failure and the mode of failure.

(7) The total time on each aircraft in the population to a given date.

Sorting, editing, and listings of the histories include the following:

(1) Sorts and lists components chronologically by serial number. Edits this listing for missing or erroneous data.

(2) Sorts and lists components chronologically by aircraft number. Edits this listing for missing or erroneous data.

(3) Lists the aircraft time for each aircraft of the population. Computes and lists for each aircraft the time accumulated since the last overhaul. Edits the listing for missing or erroneous data.

(4) Calculates and prints out the total accumulated hours.

(5) Sorts and lists all failures by failure mode, including the percentage contribution of each mode.

The plot of failure versus TSO is printed out as shown in Figure 86.

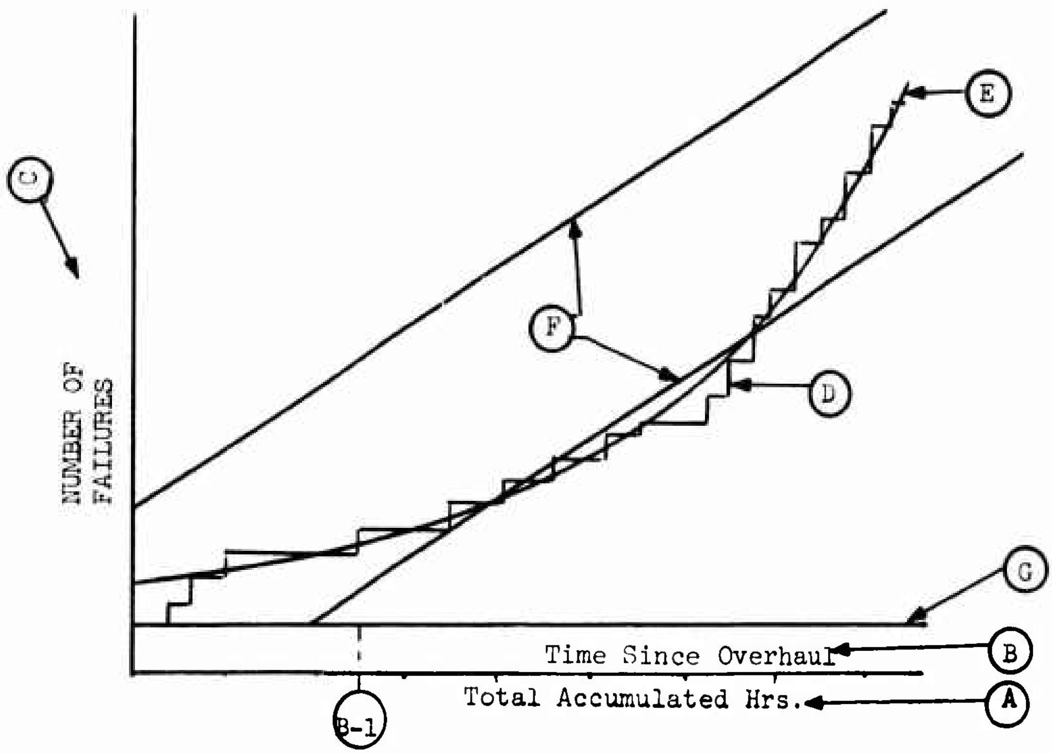


Figure 86. FRAP Failure Versus TSO Plot.

In Figure 86 the letters that appear are defined as follows:

- A = Total accumulated hours - a linear scale indicating all component time accumulated on all aircraft (including those components still in operation on an aircraft).
- B = Time since overhaul (TSO) - a nonlinear scale, aligned with the TOTAL ACCUMULATED HOURS scale such that, for example, the B-1 TOTAL ACCUMULATED HOURS reflect the total time accumulated on all components with TSO between zero and the B-1 TSO.
- C = Number of failures - a linear scale.
- D = Failures versus TSO plot - a step function plot of all component failures (or, if desired, just certain of the component's failure modes) versus the TSO at which the failures occurred.
- E = A best-fit polynominal curve - for the step function failures versus TSO plot.
- F = Kolmogorov-Smirnov (K-S) boundaries - run parallel to a straight line drawn from the origin to the last point of the failure versus TSO plot; the spacing increases with higher confidence levels and with fewer failure points.
- G = Highest operating life of all the components surveyed. This should be no greater than the maximum allowable TBO.

The probability of component survival to any given TSO is determined by FRAP as follows:

1. The instantaneous slope of the best-fit polynominal curve of the failures versus TSO plot is determined and plotted as failure rate versus TSO in Figure 87.

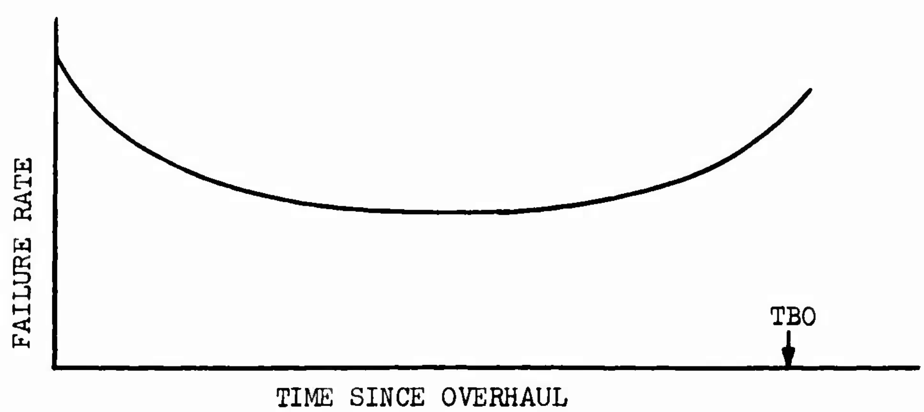


Figure 87. Failure Rate Plot.

2. Then, using the instantaneous failure rate as determined in the above plot, the probability of component survival is computed as

$$R = e^{-\int \lambda \, dt}$$

where R is the probability of survival and λ is the instantaneous failure rate. The resulting survival plot is shown in Figure 88.

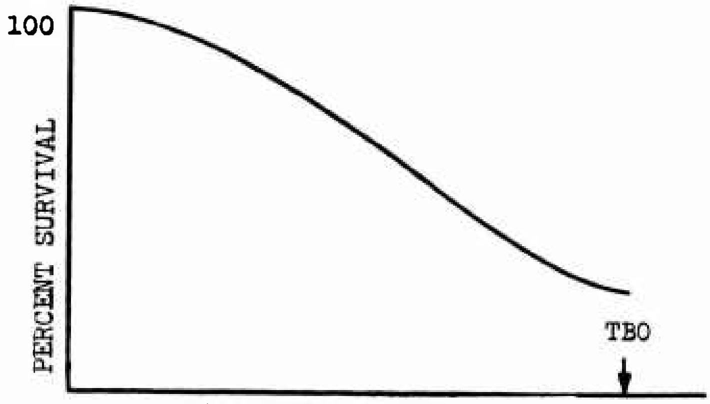


Figure 88. FRAP Survival Plot.

Use of FRAP is as follows:

1. The complete history of the component under study is input into the program.

2. The failures versus TSO plot is studied with the following considerations:

   (a) If the curve goes below the lower K-S boundary, we have a given level of confidence that the failure rate of the component is increasing with time. This indicates a wearout phenomenon of the component within the scheduled overhaul period. This phenomenon may be caused by one or a few wearout failure modes that become predominant at some given TSO.

   (b) If the curve goes above the upper K-S boundary, we have a given level of confidence that the failure rate of the component is decreasing with time. This indicates a relatively high probability of early failure, possibly due to poor quality control or failures resulting from handling or maintenance errors.

   (c) If the curve stays within the boundaries and we have sufficient data points, we can be reasonably sure that the failure rate of the component is nearly constant with time.

3. The list of failures by failure mode is studied to determine the significant modes of failure. If the effect of any given mode

(or any combination of modes) of failure is desired, a failure versus TSO plot is made for that mode(s) and studied as indicated in (2) above. Conversely, by excluding a certain mode(s), the effect of eliminating this mode(s) can be studied.

4. If it is desirable to study the economic feasibility of changing the component TBO, the following should be considered:

   (a) As long as the failure rate of a component remains constant with time, it will not be economically advantageous to conduct a scheduled overhaul of the component. The probability of failure immediately after overhaul is as great as the probability of failure immediately prior to overhaul. Unscheduled maintenance and mission aborts are not reduced; scheduled maintenance is increased. Additional costs are incurred due to spare parts requirements shipping requirements, etc.

   (b) If the failure rate of a component decreases with time, it is not economically feasible to overhaul. The probability of failure is greatest immediately after installation.

   (c) If the failure rate of a component increases sharply at some point in its life, it may be economically feasible to allow for a scheduled overhaul just prior to the sharp increase. This could effectively reduce unscheduled maintenance and mission aborts.

   (d) If the goal is to extend the TBO for a component, then redesign should be considered for those modes of failure which may cause the component failure rate to increase.

5. If it is desired to determine the percentage of the component which will survive to any given time since overhaul (or to compare the existing component survival to the survival after any given mode(s) of failure is eliminated), the FRAP survival plot is studied. The percentage of survival at any given TSO (up to the highest operating life) can be read directly.

TYPICAL APPLICATIONS

The following pages provide a summary of the findings of FRAP as applied to four major dynamic components of the CH-3C/HH-3E aircraft: the tail gearbox, the intermediate gearbox, the main rotor head, and the tail rotor head. The basic curve shapes determined for each of these components are very similar to the comparable components on other aircraft studied by Sikorsky.

Intermediate Gearbox

The failure versus TSO plot of the intermediate gearbox (all modes of failure considered) did not fall outside of either of the 90-percent confidence K-S boundaries (See Figure 89). It was qualitatively noted, however, that the slope of the curve (hence, the failure rate) was greatest

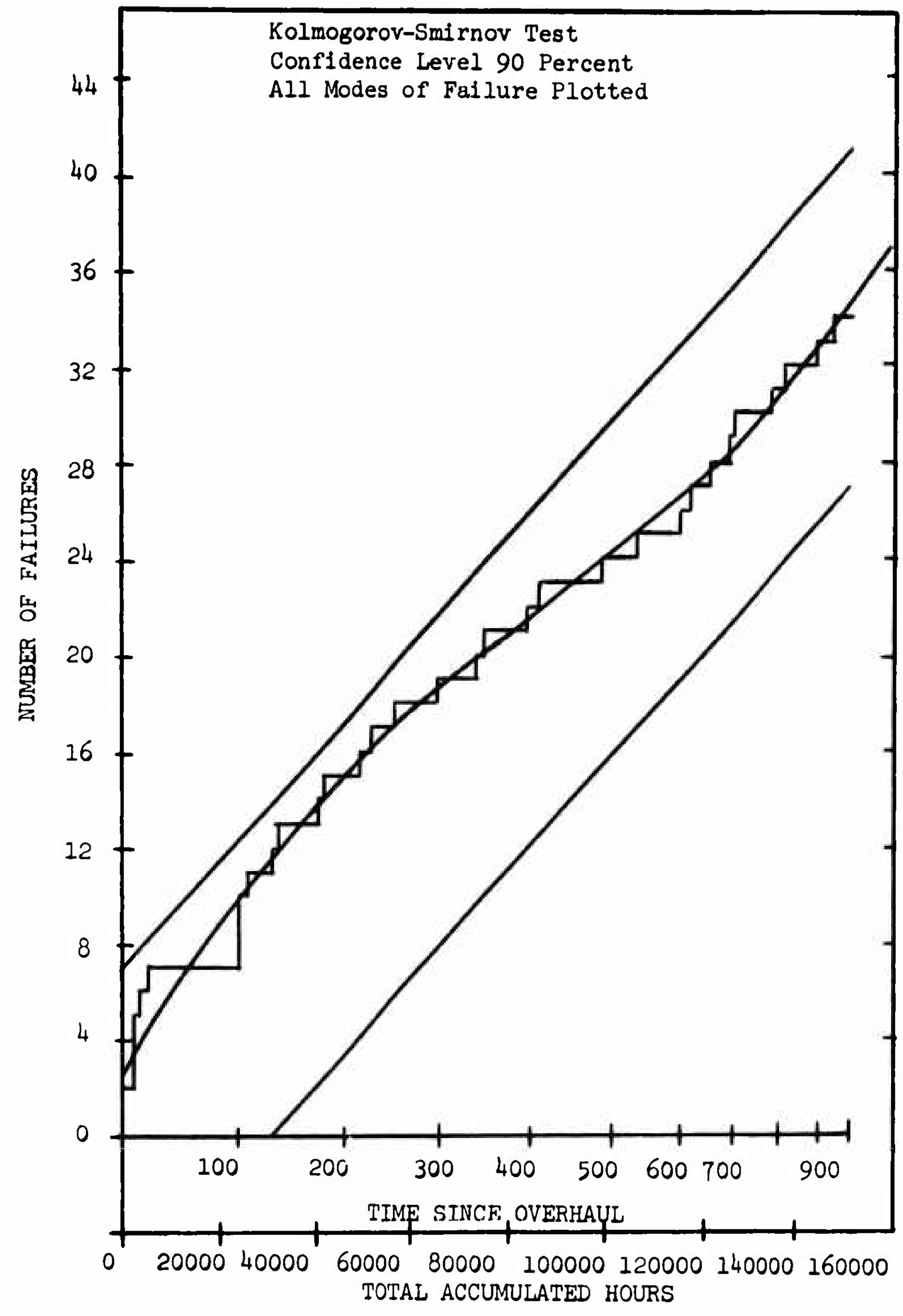


Figure 89. FRAP Failure Versus TSO: CH-3C/HH-3E Intermediate Gearbox.

during the first 200 hours TSO. In order to determine what caused this phenomenon, the failure mode summary was studied. It was determined that the "input shaft seal leakage" failure mode was by far the most significant (more than 40 percent of the failures). In order to determine what effect this failure mode had upon the total component failure rate, a failure versus TSO plot was made for just this one mode of failure (Figure 90) and for all modes except this one mode of failure (Figure 91). It is noted from Figure 90 that the failure versus TSO plot for the "input seal leakage" mode of failure goes above the upper K-S boundary, indicating that with 90-percent confidence we can state that this mode of failure has a decreasing failure rate. This implies that the probability of input seal failure is greatest during the first 200 hours TSO. This may be due to poor seal quality control or damage during handling or installation.

Possible means of preventing this phenomenon include:

(1) Tighter quality control

(2) Improved handling/installation provisions

(3) Use of a field removable seal (allowing seal replacement without removal of the entire gearbox)

If this phenomenon could be eliminated, the K-S failure versus TSO plot shown in Figure 91 would apply. As may be seen, this failure versus TSO plot stays well within the K-S boundaries, implying a reasonably constant failure rate through the limits of our existing experience.

In order to determine the effects upon gearbox survival to a given TSO for the existing configuration and for a configuration with the "input shaft seal leakage" eliminated, failure rate plots (Figures 92 and 94) and survival plots (Figures 93 and 95)were made. It is noted that with the elimination of this mode of failure, the gearbox percentage of survival to overhaul (1000 hours) could be increased from 80 percent to 88 percent.

Whether the "shaft seal leakage" mode of failure is corrected or not, it can be seen from Figures 89 and 91 that, from an economics standpoint, there can be nothing gained in removing a component for a scheduled overhaul through the existing 1000-hour TBO. The probability of failure immediately after overhaul is equal to or greater than the probability of failure immediately before overhaul. The cost of unscheduled overhauls is not decreased while the cost of scheduled overhauls is incurred. A reasonable TBO program, for this component, from an economics standpoint, would be to continuously increase the TBO while monitoring the effect of the increase upon the failure rate. As long as an increase in failure rate was not observed, it would be economically sound to increase the TBO.

Tail Gearbox

The failure versus TSO plot of the tail gearbox (all modes of failure considered) fell well within the 90-percent confidence K-S boundaries (see Figure 96). This implies a reasonably constant failure rate through the limits of our existing experience. From the failure mode summary, it was

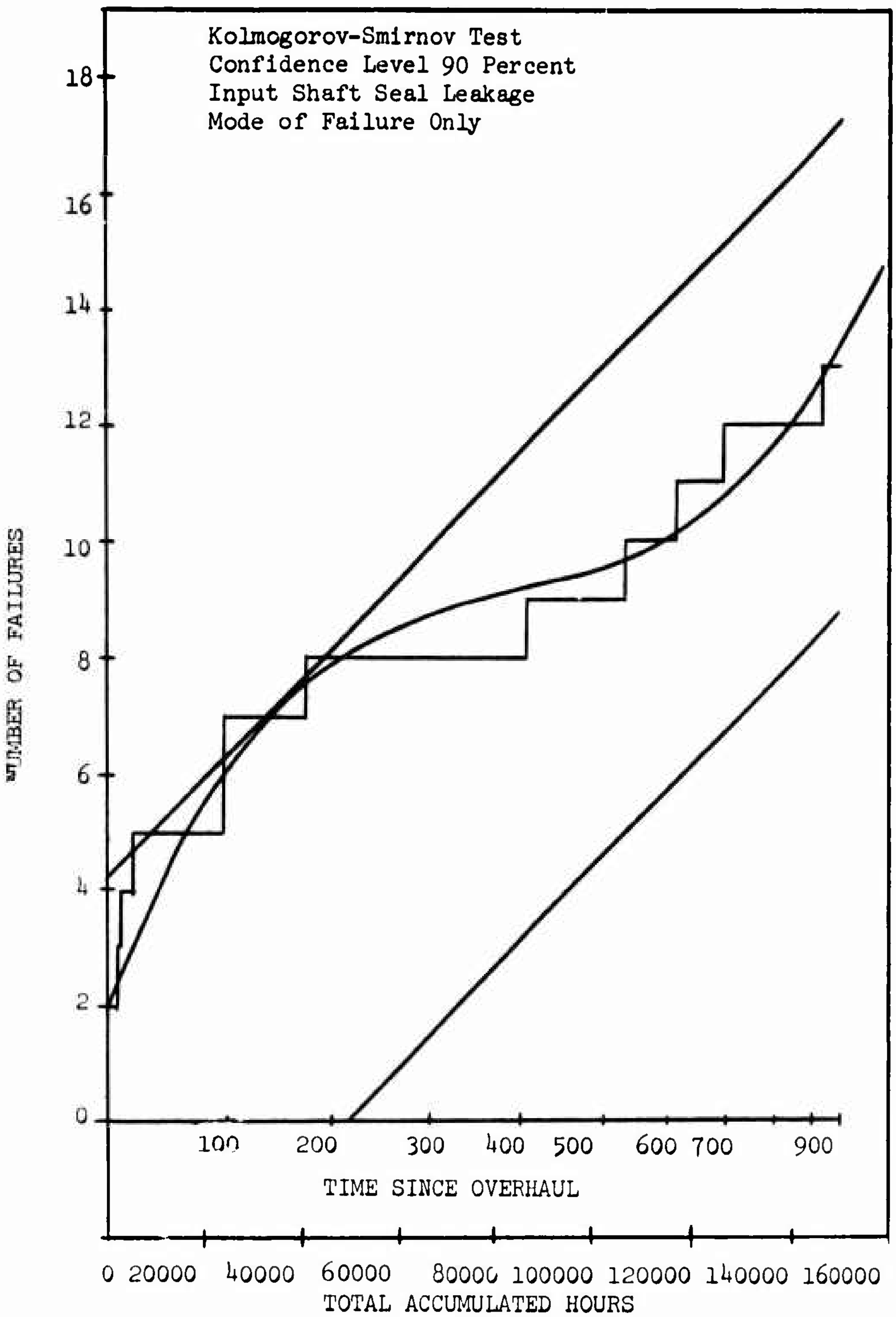


Figure 90. FRAP Failure Versus TSO: CH-3C/HH-3E Intermediate Gearbox.

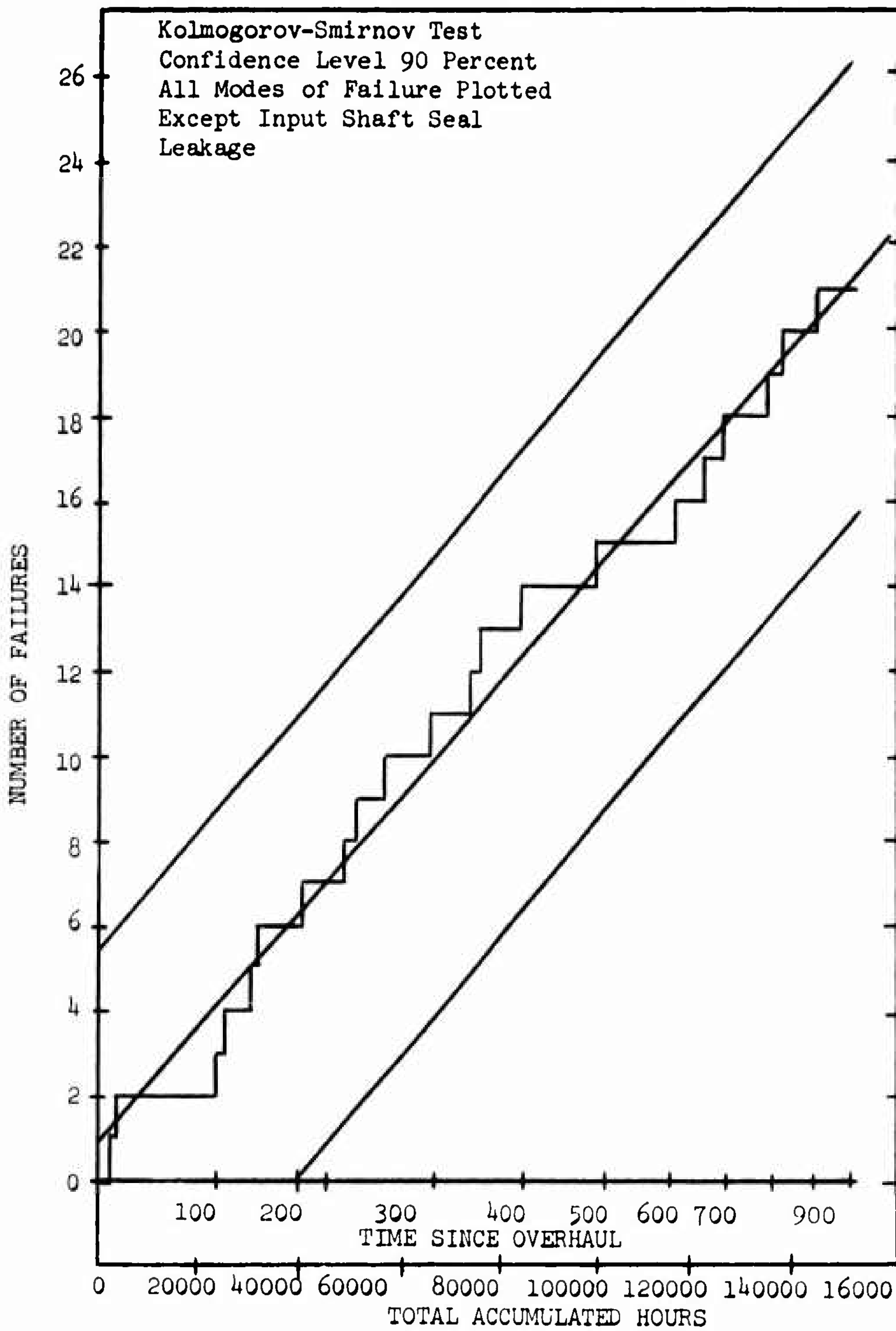


Figure 91. FRAP Failure Versus TSO: CH-3C/HH-3E Intermediate Gearbox.

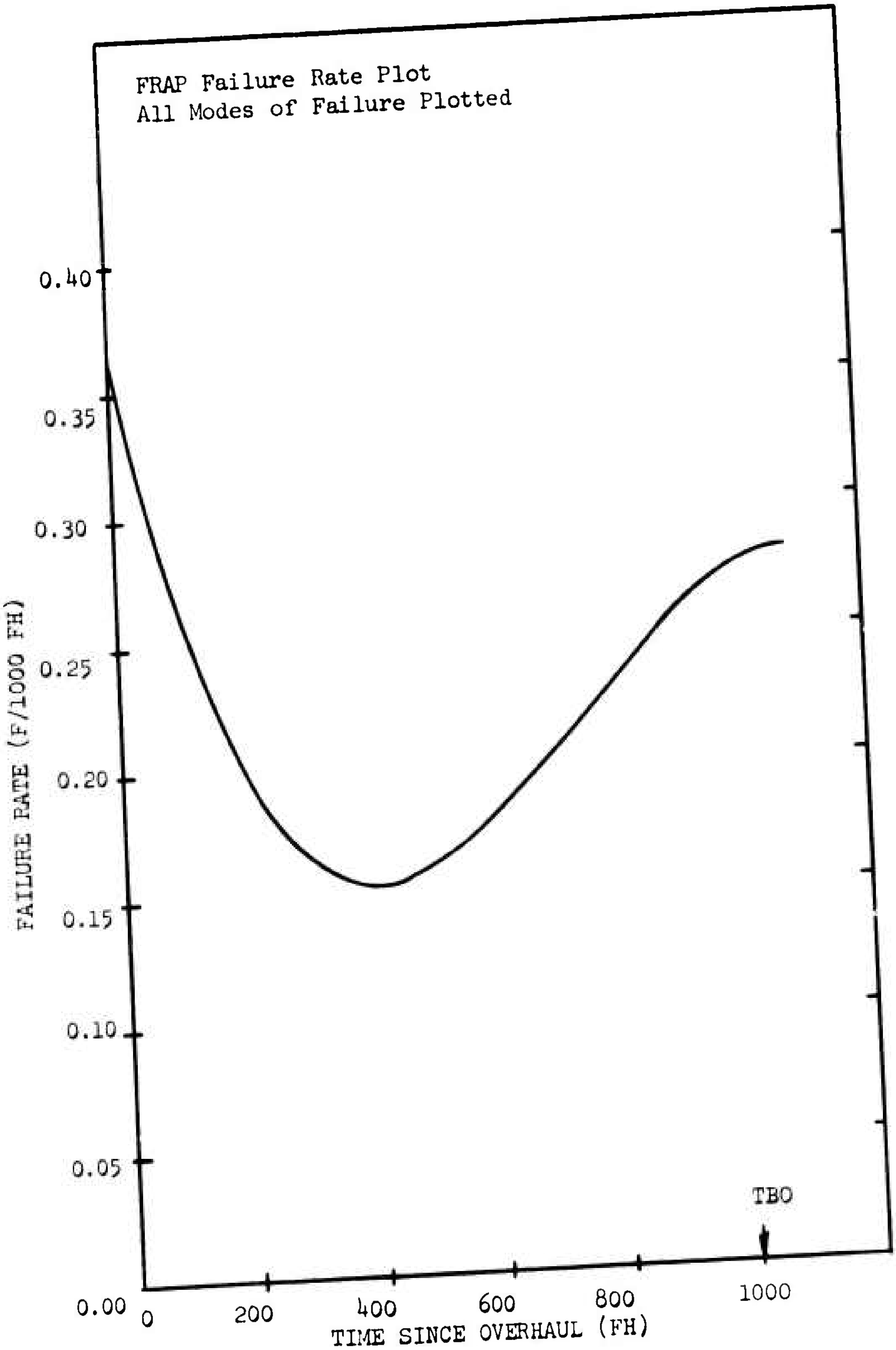


Figure 92. FRAP Failure Rate: CH-3C/HH-3E Intermediate Gearbox.

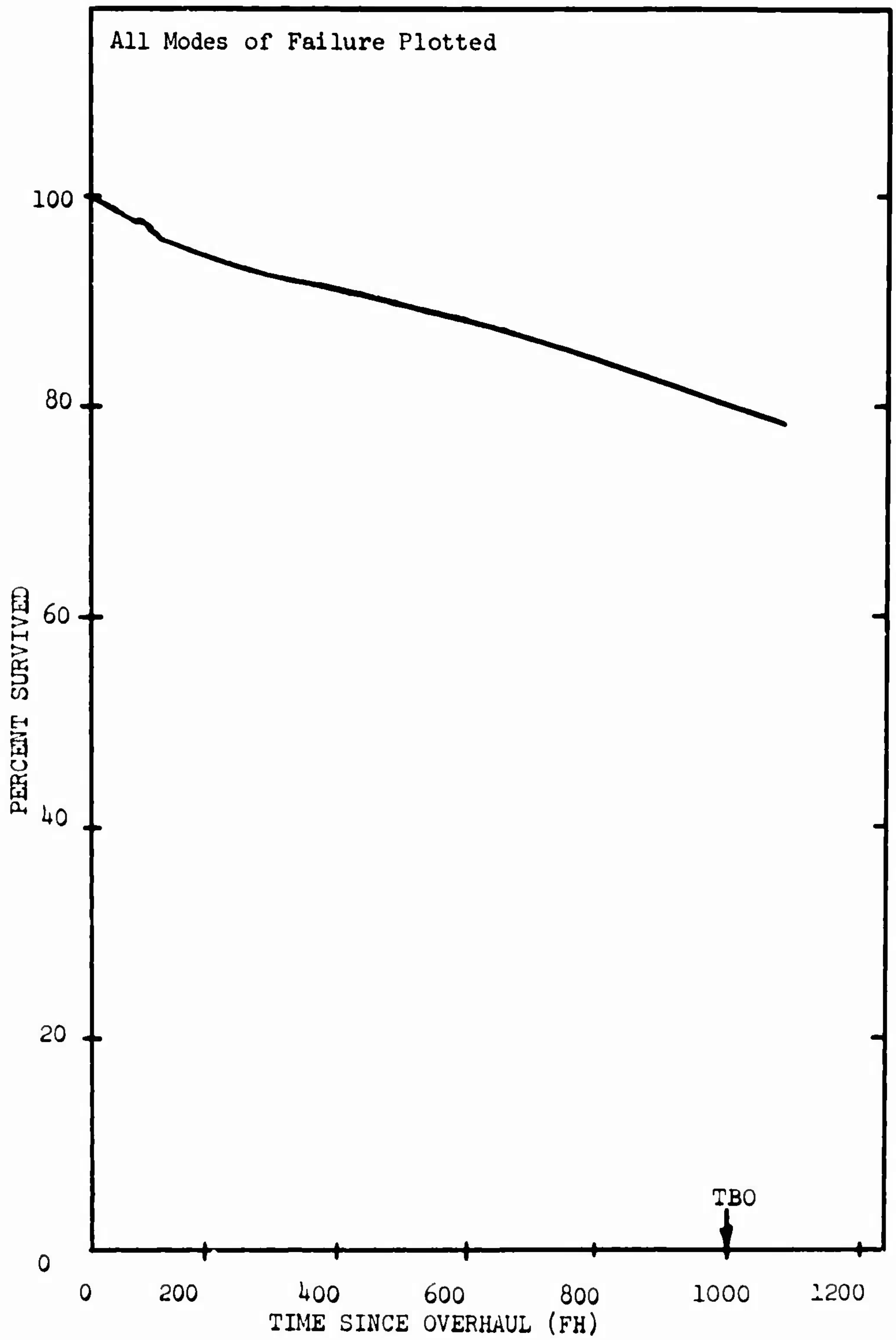


Figure 93. FRAP Survival Plot: CH-3C/HH-3E Intermediate Gearbox.

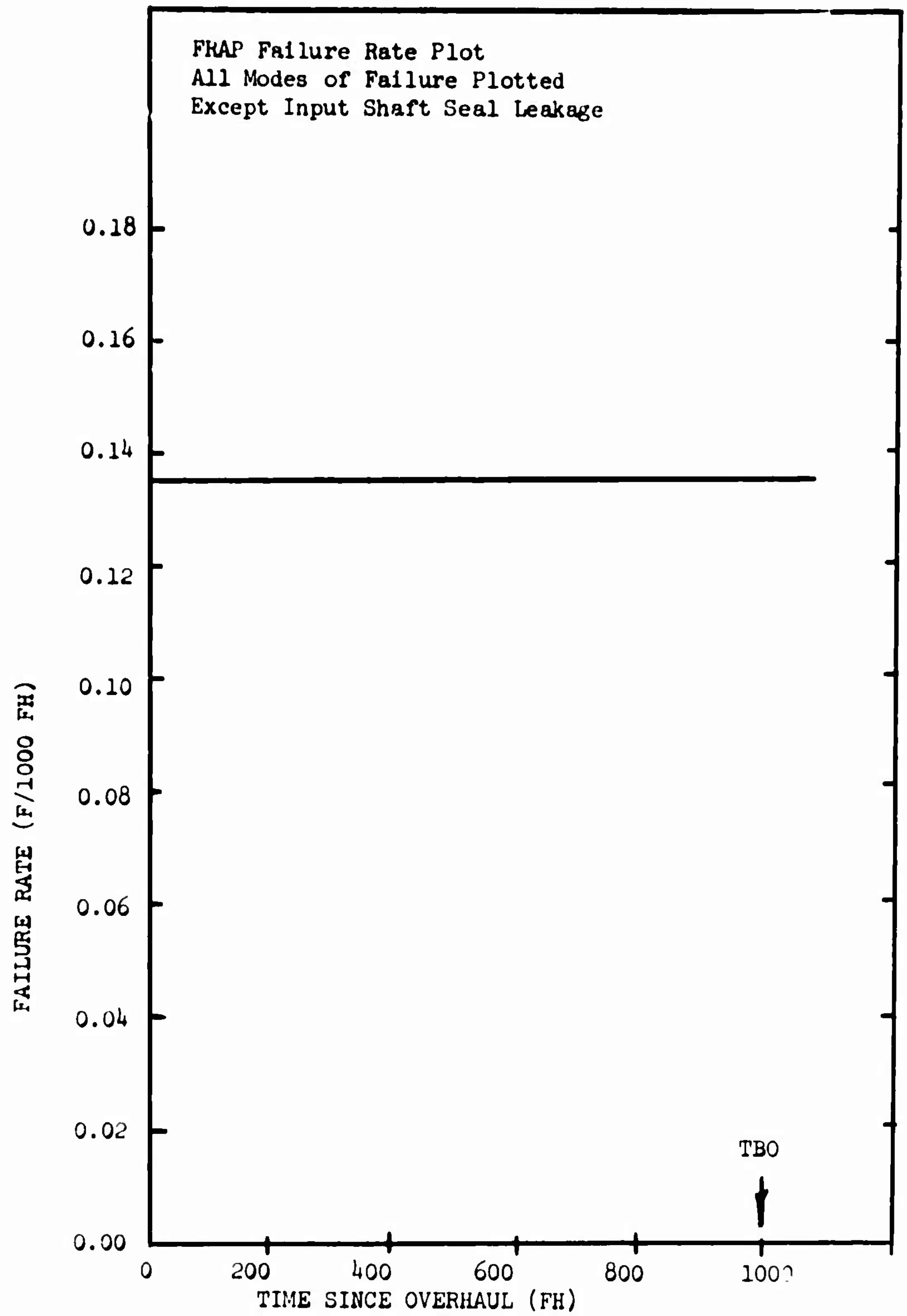


Figure 94. FRAP Failure Rate: CH-3C/HH-3E Intermediate Gearbox.

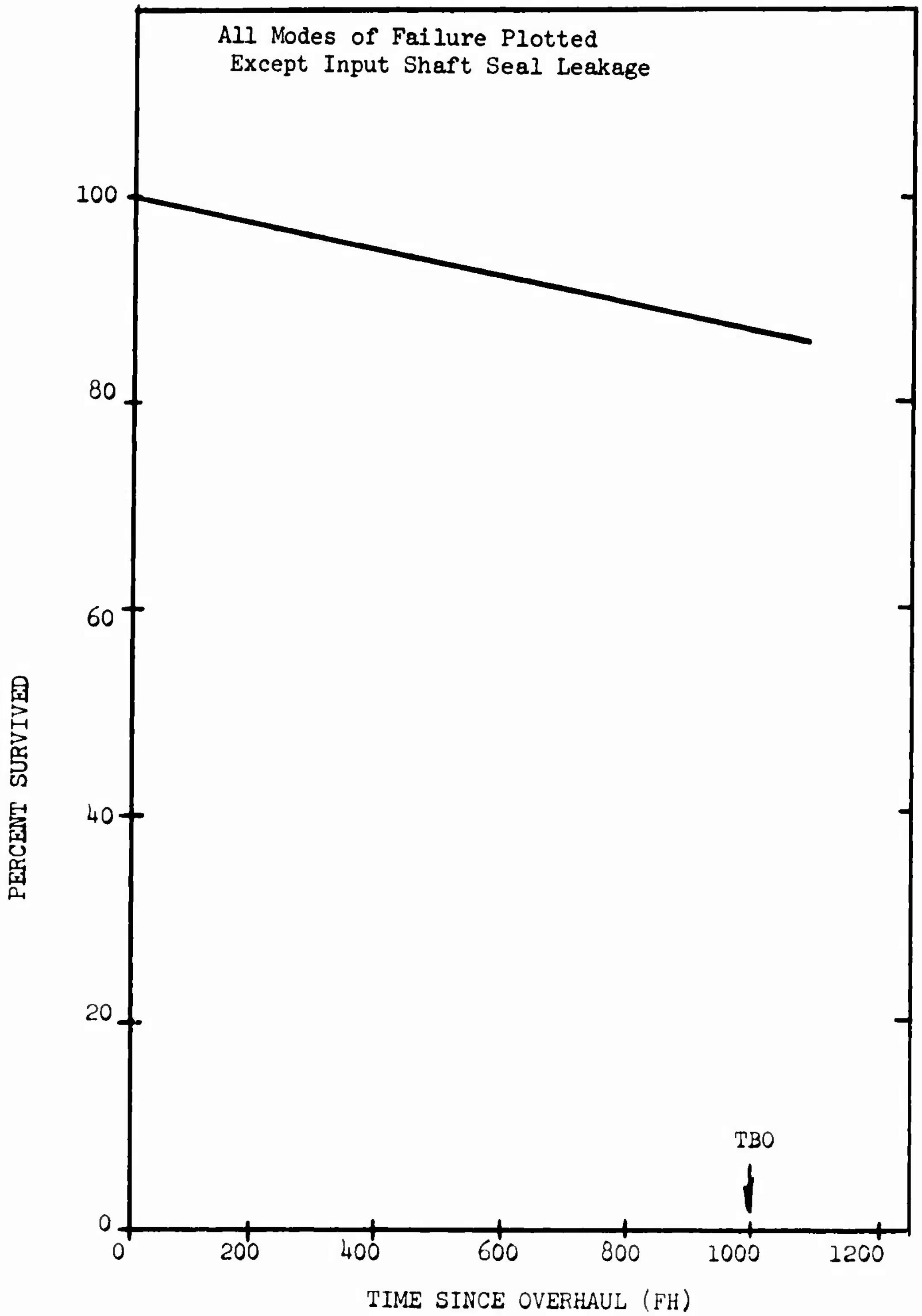


Figure 95. FRAP Survival Plot: CH-3C/HH-3E Intermediate Gearbox.

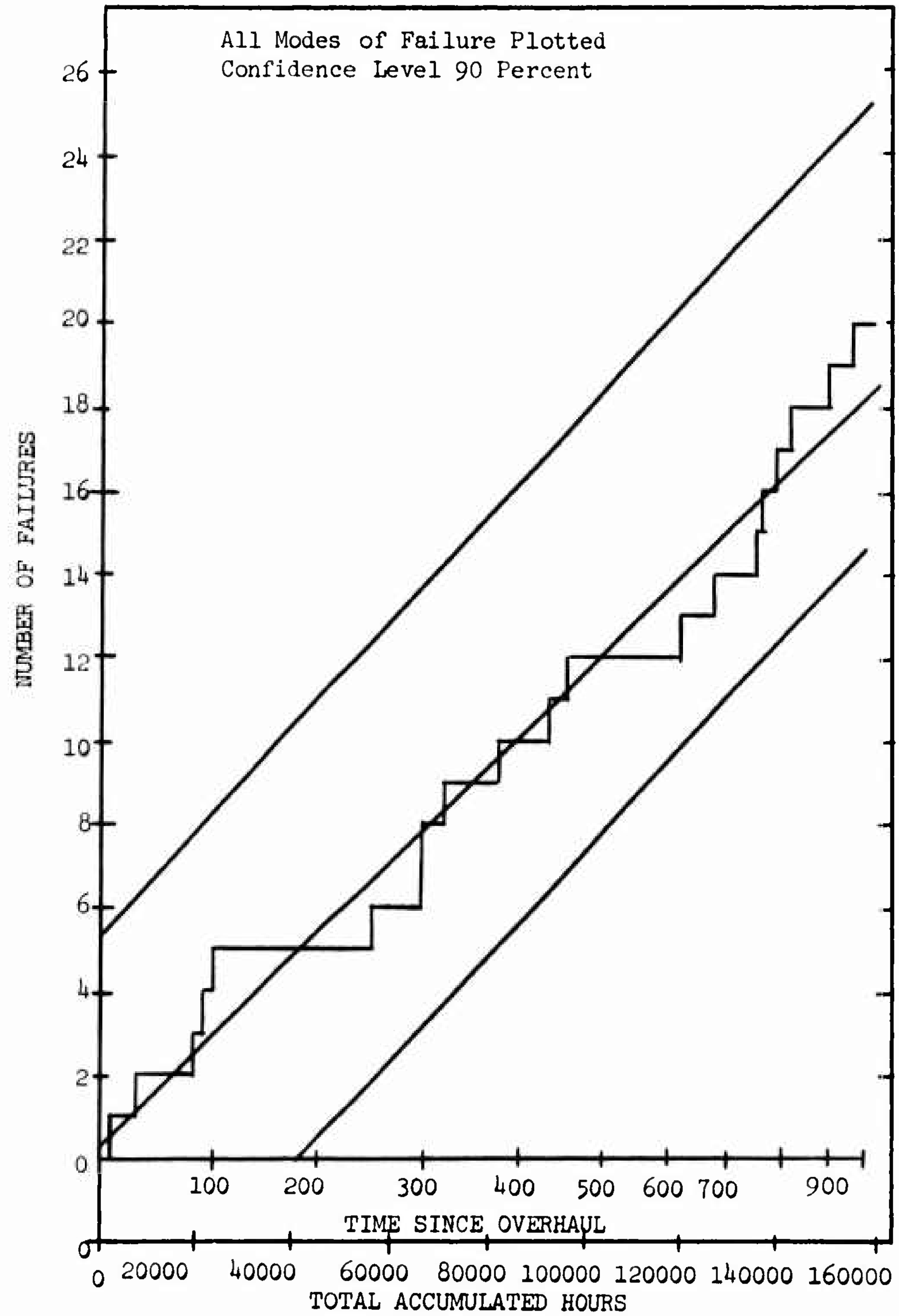


Figure 96. FRAP Failure Versus TSO: CH-3C/HH-3F Tail Gearbox.

determined that there were no significant modes of failure influencing this component. A failure rate plot (Figure 97) and a survival plot (Figure 98) were made. It was determined that with the existing configuration, 89 percent of the gearboxes survive to the TBO (1000 hours).

As may be seen from Figure 96, from an economics standpoint, there can be nothing gained in removing a component for a scheduled overhaul through the existing 1000 hours TBO. The comments concerning the intermediate gearbox TBO establishment apply to the tail gearbox.

Main Rotor Head

The failure versus TSO plot of the main rotor head (all modes of failure plotted) fell well below the lower 90 percent confidence K-S boundary (see Figure 99). Hence, we can state with 90 percent confidence that the failure rate increases with time.

The failure mode summary was studied, and the following modes of failure were felt to be the most significant:

(1) Sleeve and spindle seal leakage

(2) Vertical hinge seal leakage

(3) Swashplate assembly/swashplate bearing wear

(4) Sleeve and spindle bearing failure

(5) Sleeve and spindle spacer scored

Failure versus TSO plots for the above failure modes are shown in Figures 100 through 104. The "sleeve and spindle seal leakage" and the "swashplate/swashplate bearing wear" modes of failure exhibit significant wearout characteristics. On the other hand, the "vertical hinge seal leakage", the "sleeve and spindle bearing failure", and the "sleeve and spindle spacer scored" modes exhibit a reasonably constant failure rate.

The failure mode summary was then studied further to determine the effect of the remaining failure modes. These general categories of failure modes remained:

(1) Undefined leakage

(2) Miscellaneous modes, each with only one or two occurrences

(3) Undefined miscellaneous modes

The "undefined leakage" mode was included with "sleeve and spindle seal leakage" and plotted as shown in Figure 105. This mode accentuates the wearout phenomenon of the "sleeve and spindle seal leakage". The miscellaneous modes and the undefined miscellaneous modes were then plotted as shown in Figures 106 and 107. Each of these also exhibits wearout characteristics.

The increasing failure rate of the main rotor head infers that possibly

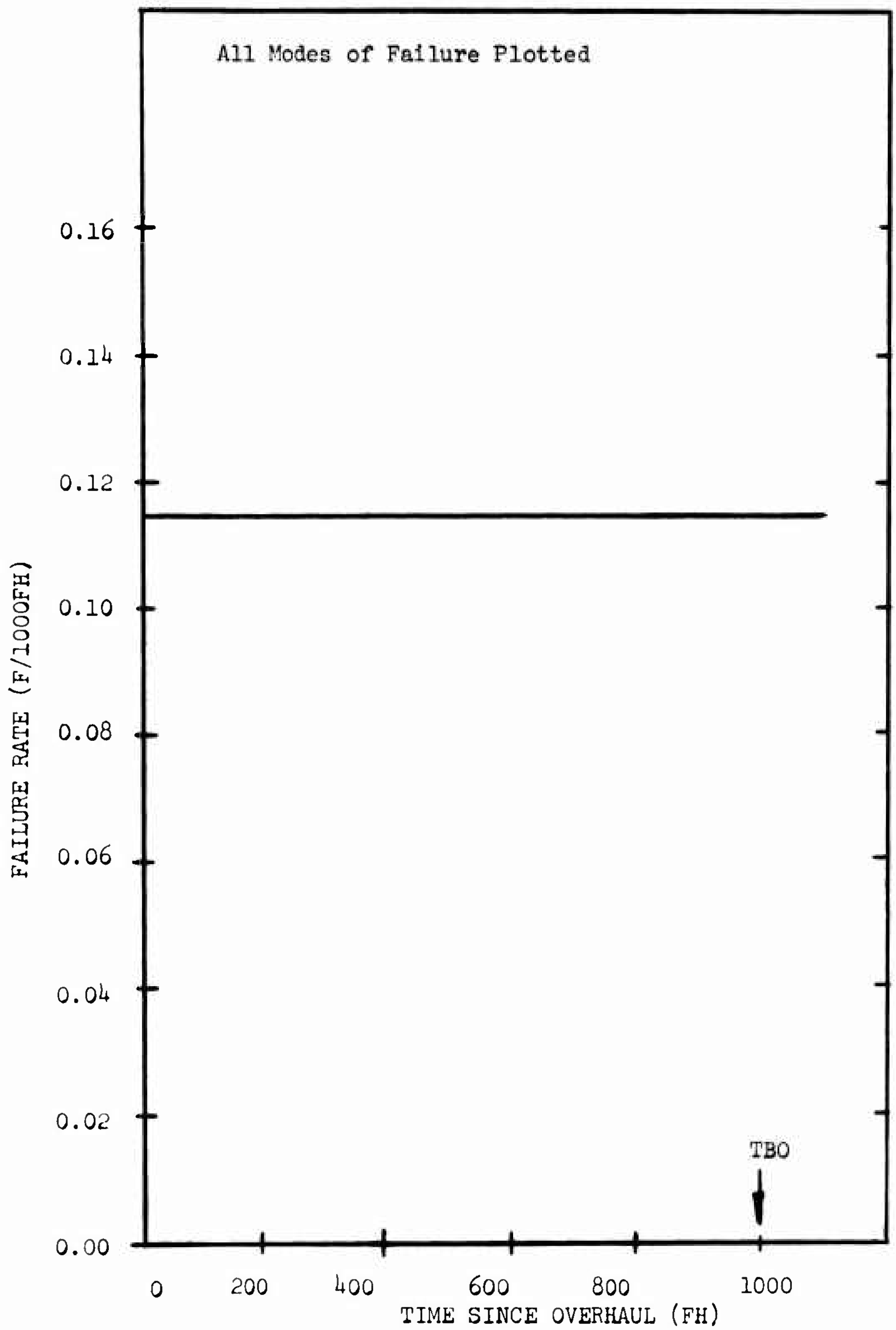


Figure 97. FRAP Failure Rate: CH-3C/HH-3E Tail Gearbox.

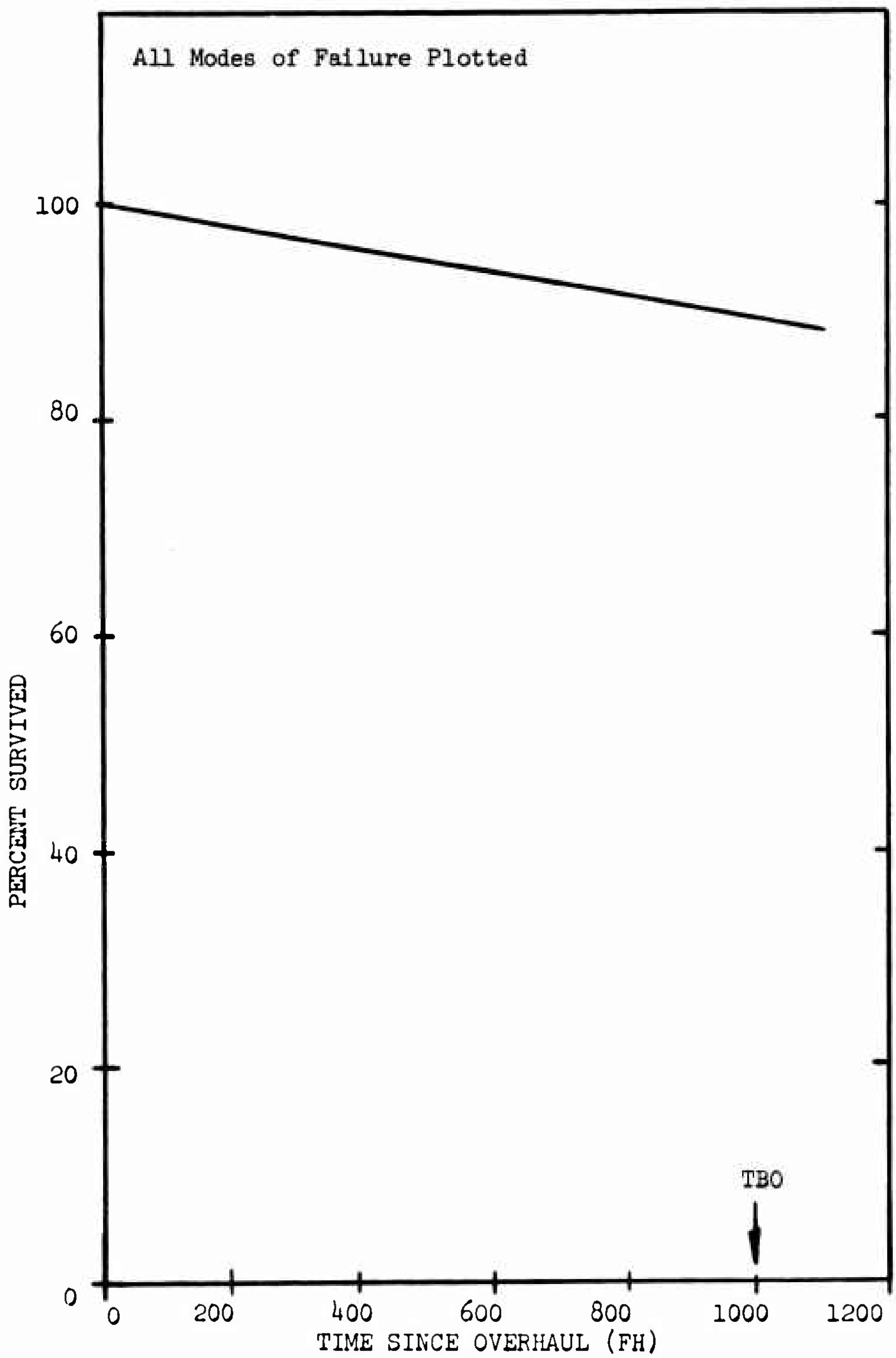


Figure 98. FRAP Survival Plot: CH-3C/HH-3E Tail Gearbox.

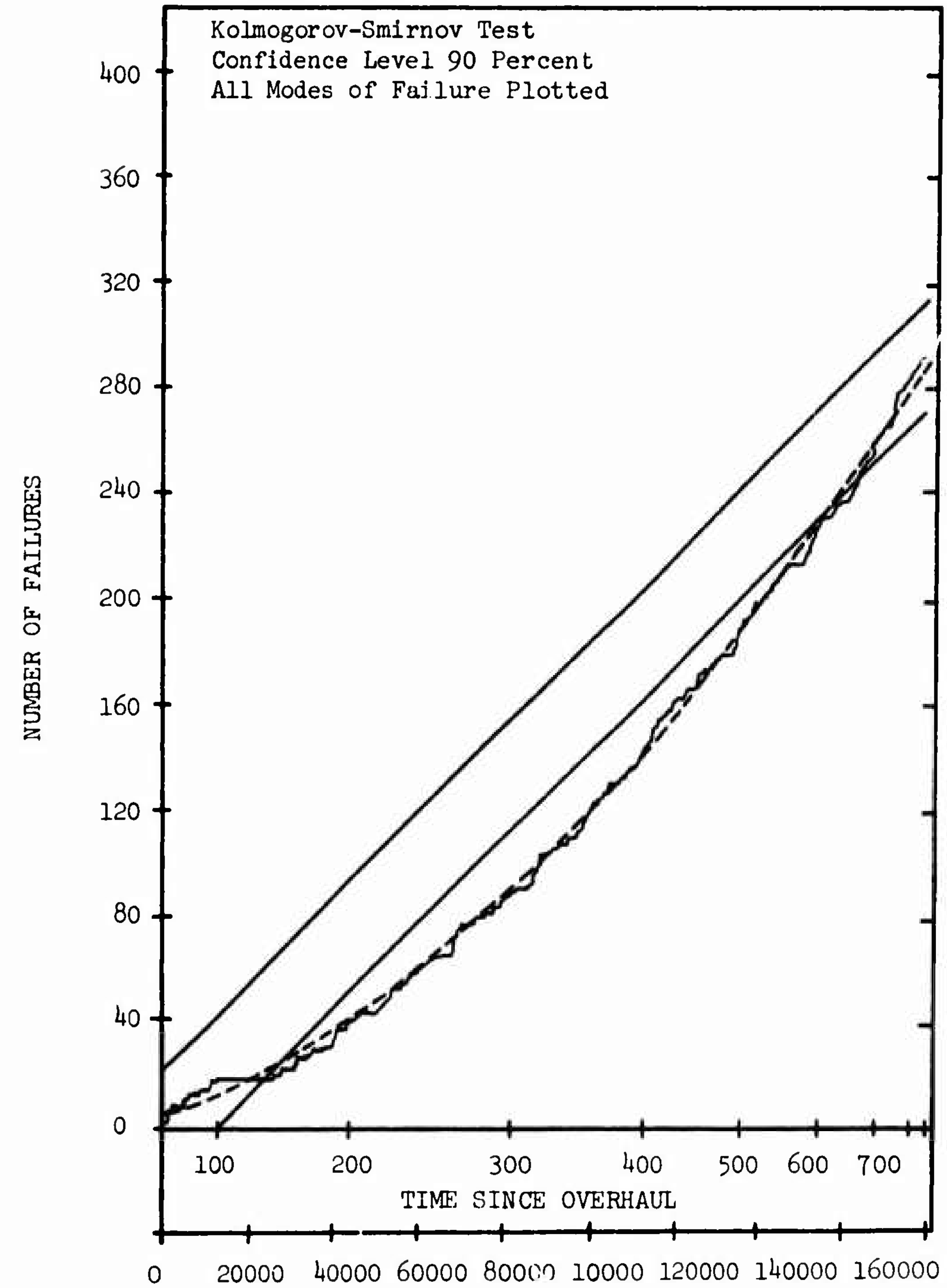


Figure 99. Failure Versus TSO: CH-3C/HH-3E Main Rotor Head.

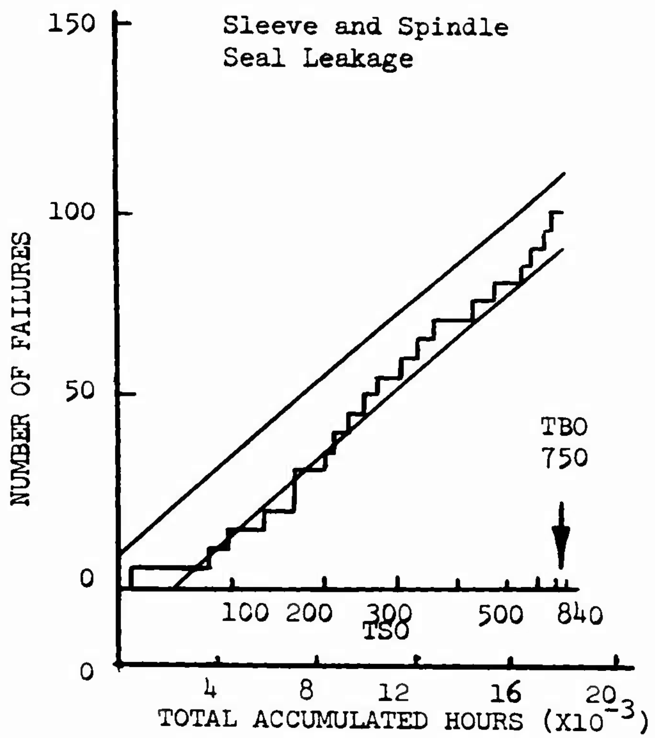


Figure 100. Failure Versus TSO: CH-3C/HH-3E Main Rotor Head.

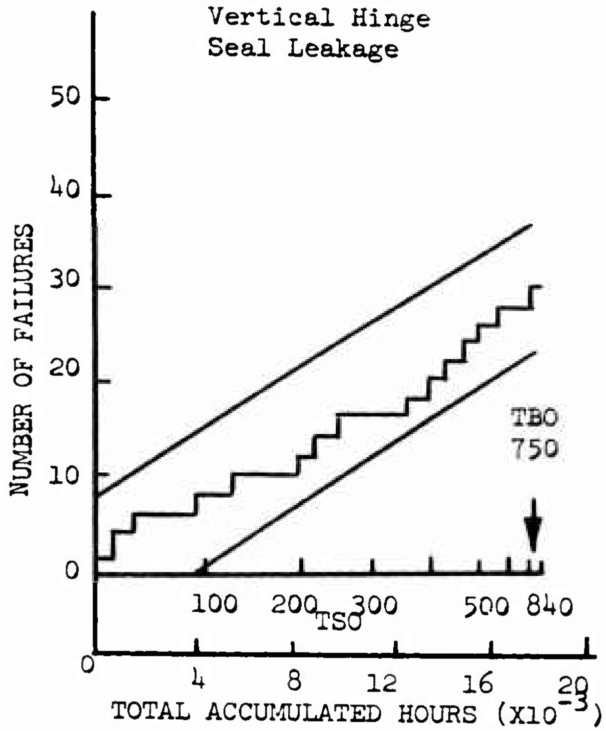


Figure 101. Failure Versus TSO: CH-3C/HH-3E Main Rotor Head.

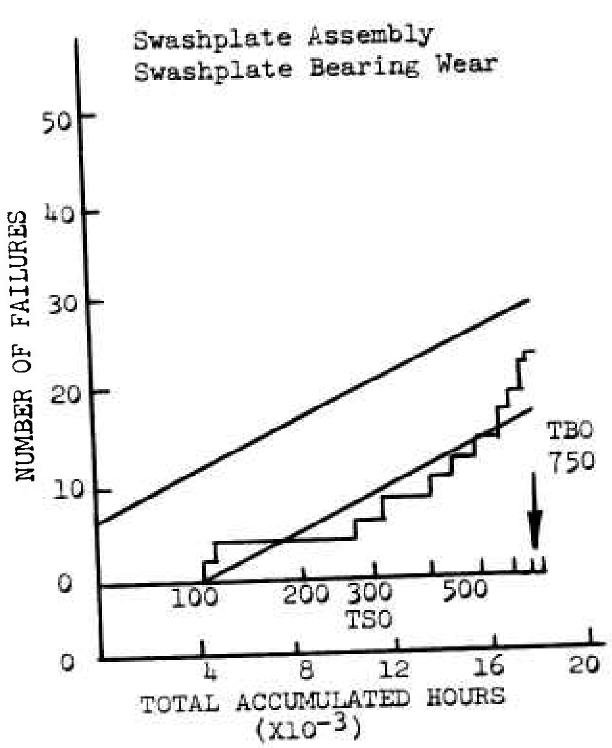


Figure 102. Failure Versus TSO: CH-3C/HH-3E Main Rotor Head.

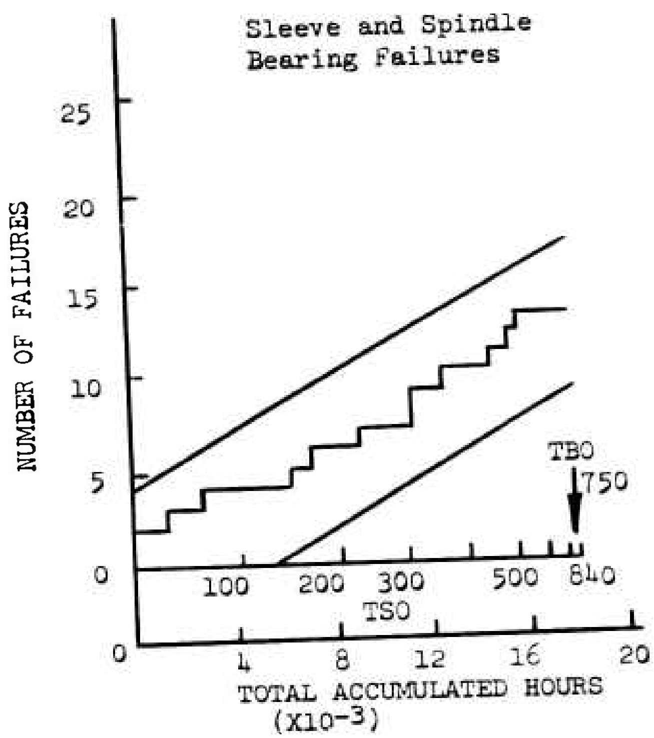


Figure 103. Failure Versus TSO: CH-3C/HH-3E Main Rotor Head.

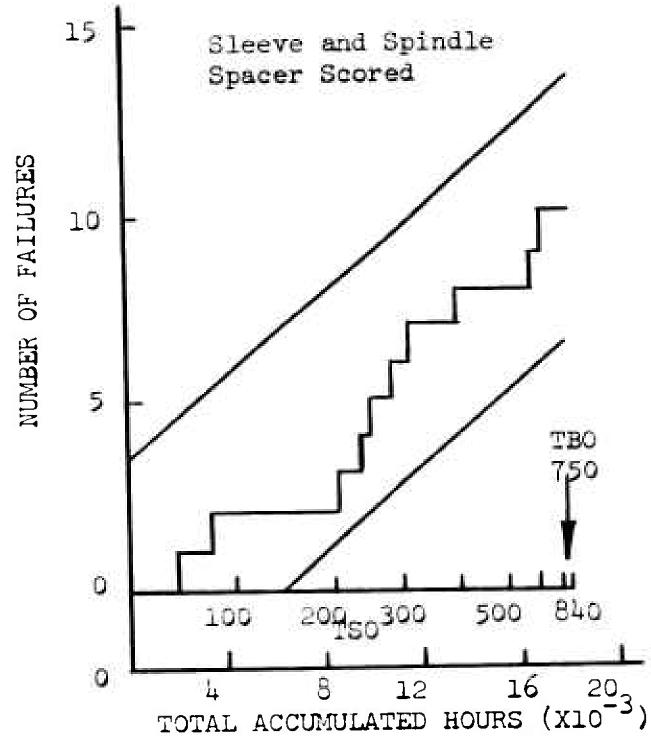


Figure 104. Failure Versus TSO: CH-3C/HH-3E Main Rotor Head.

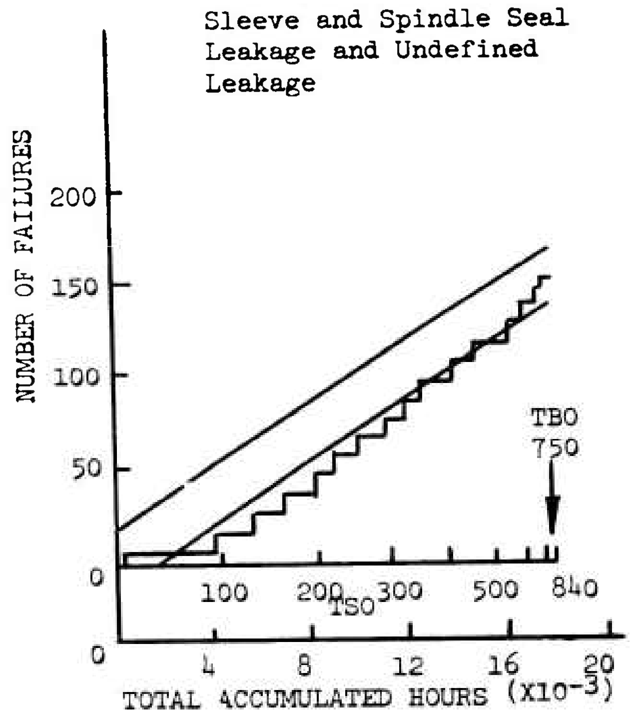


Figure 105. Failure Versus TSO: CH-3C/HH-3E Main Rotor Head.

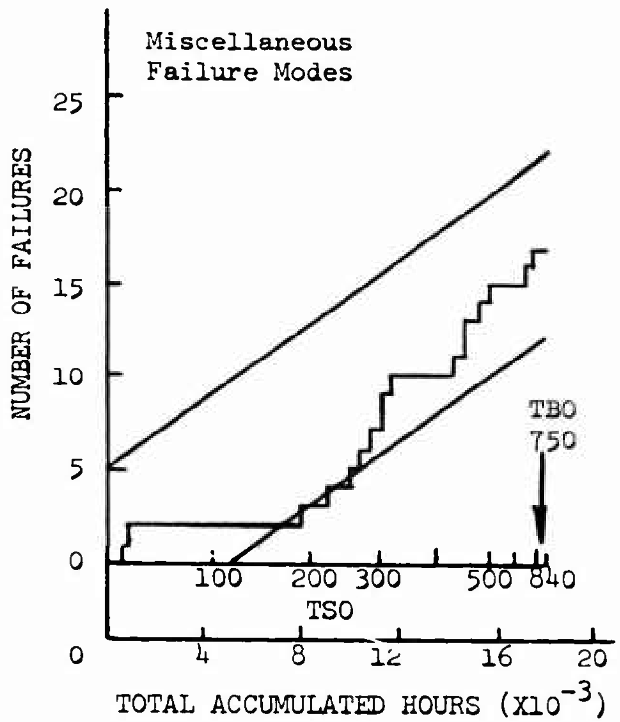


Figure 106. Failure Versus TSO:
CH-3C/HH-3E
Main Rotor Head.

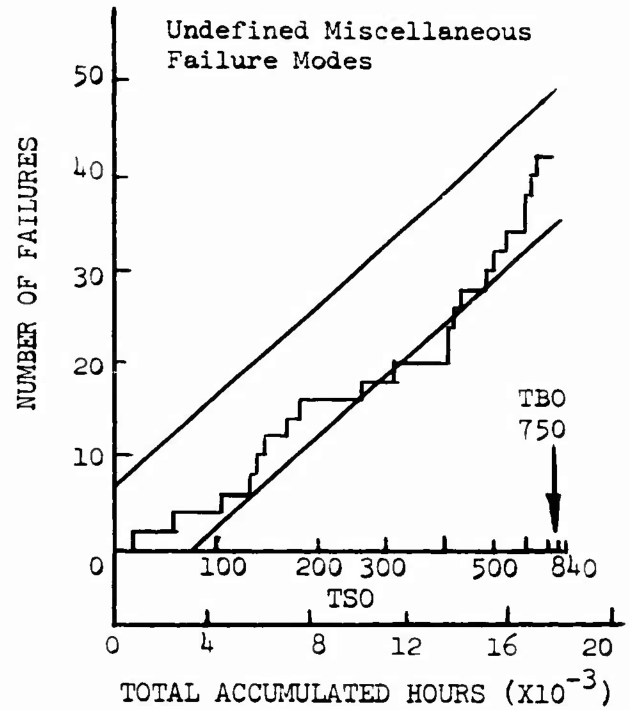


Figure 107. Failure Versus TSO:
CH-3C/HH-3E
Main Rotor Head.

there is a point at which it is most feasible (economically) to overhaul. However, there is no point at which a main rotor failure rate rises sharply. Instead, as seen in Figure 99 the failure rate increases gradually and continuously. There is, therefore, no obvious point at which a scheduled overhaul would be economically feasible.

The failure rate plot (Figure 108) and the survival plot (Figure 109) reflect that 24 percent of the rotor heads presently survive to the existing TBO (750 hours). With the indication of an increasing failure rate, it is reasonably projected that the probability of survival would drop off sharply beyond the existing TBO. As the probability of survival approaches zero, we have very few rotor heads removed for a scheduled overhaul; hence, our policy becomes, in fact, that of an "on-condition" philosophy. An extension of the TBO beyond 750 hours would therefore reap diminishing economic benefits.

The most logical TBO extension program for this type of component would be one of redesign. The redesign should be aimed at those problems most drastically affecting the rotor head survival. This can be accomplished by first attacking those problems with increasing failure rates and then those with a very high constant failure rate. These designs, after proper debugging, can be monitored, and the procedures outlined in this report can be reiterated until a feasible TBO extension can be justified.

Tail Rotor Head

The failure versus TSO plot of the tail rotor head (all modes of failure plotted) fell well below the lower 90 percent confidence K-S boundary (see Figure 110). Hence, we can state with 90 percent confidence that the failure rate increases with time.

The failure mode summary was studied, and the following modes of failure were felt to be the most significant:

(1) Sleeve and spindle bearing failures

(2) Sleeve and spindle seal leakage

(3) Sleeve and spindle seal area scored

Failure versus TSO plots for the above failure modes are shown in Figures 110 through 112. It is noted that they all exhibit wearout characteristics.

The failure mode summary was then studied further to determine the effect of the remaining failure modes. These categories of failure modes remained:

(1) Undefined leakage

(2) Oil reservoir cover cracked

(3) Hub hinge seal leakage

(4) Miscellaneous wear failure modes

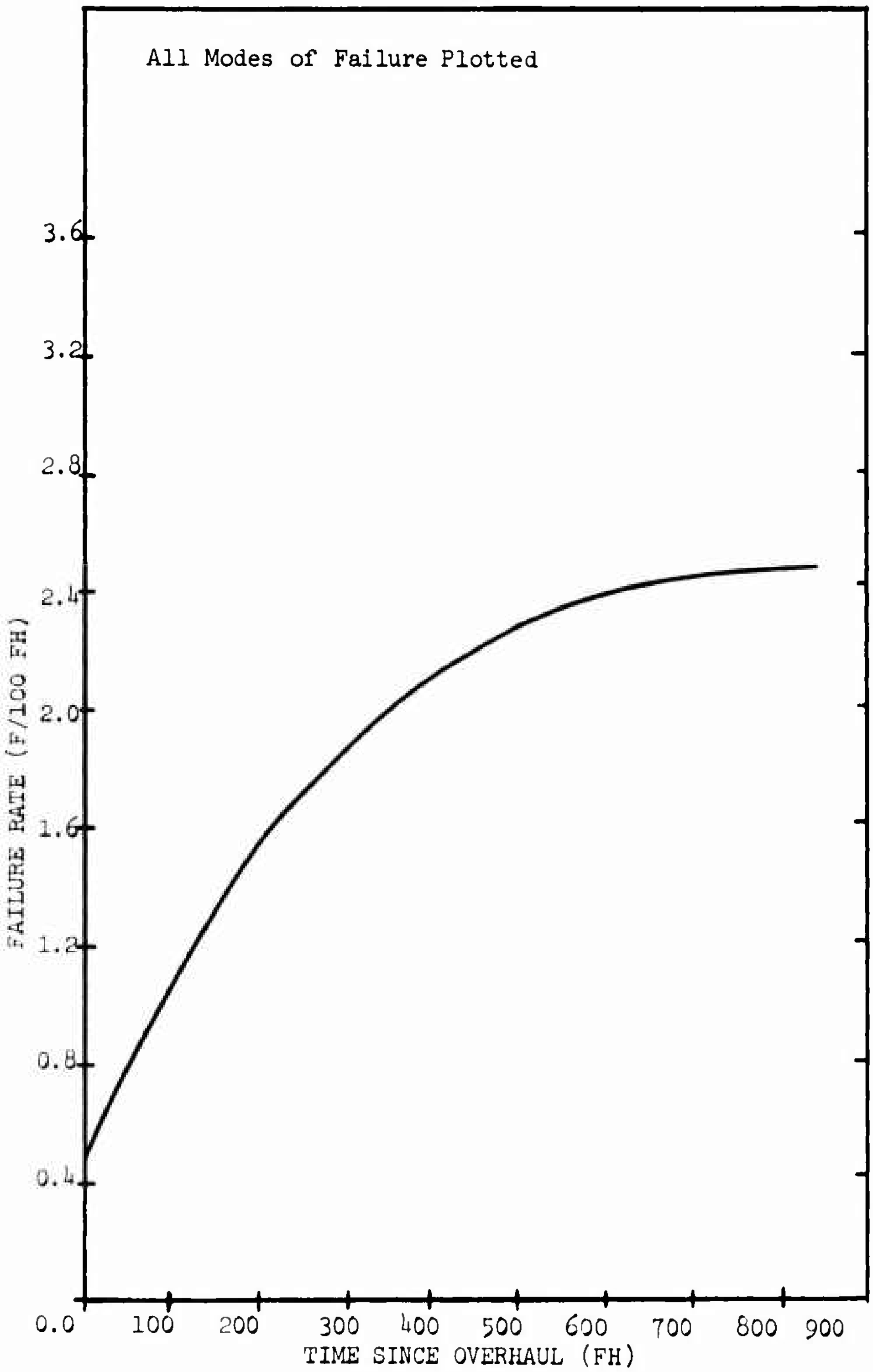


Figure 108. FRAP Failure Rate: CH-3C/HH-3E Main Rotor Head.

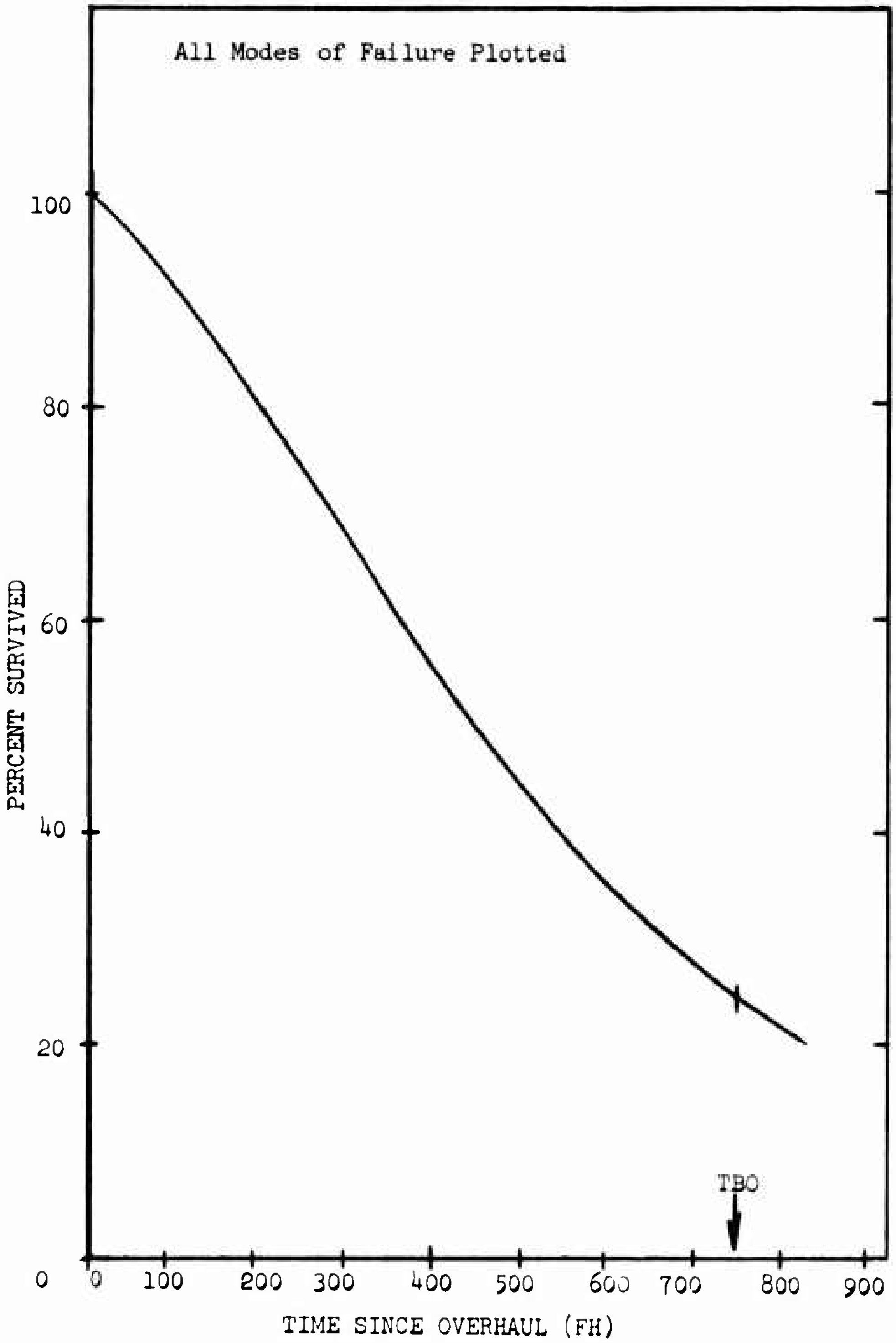


Figure 109. FRAP Survival Plot: CH-3C/HH-3E Main Rotor Head.

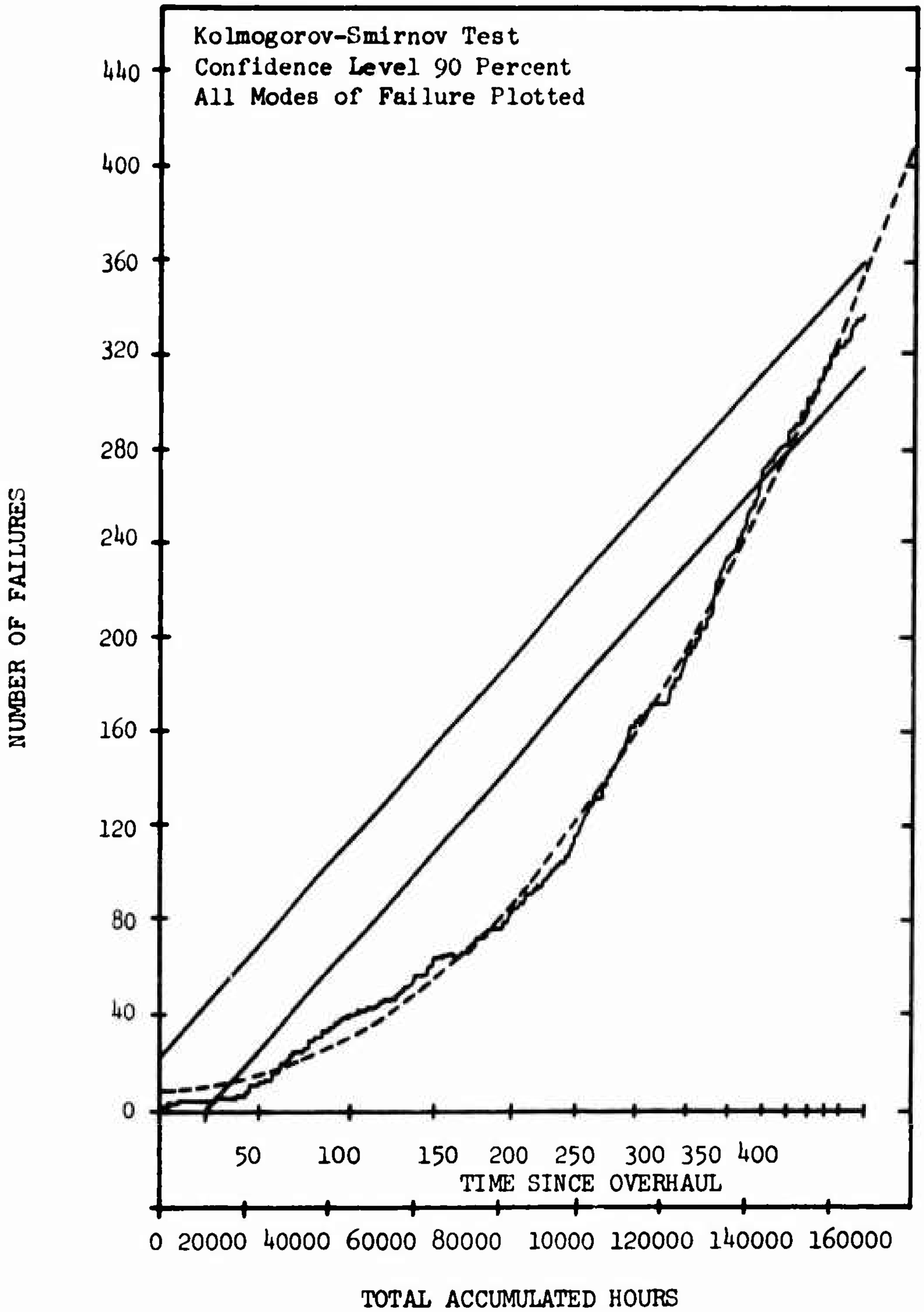


Figure 110. FRAP Failure Versus TSO:
CH-3C/HH-3E Tail Rotor Head.

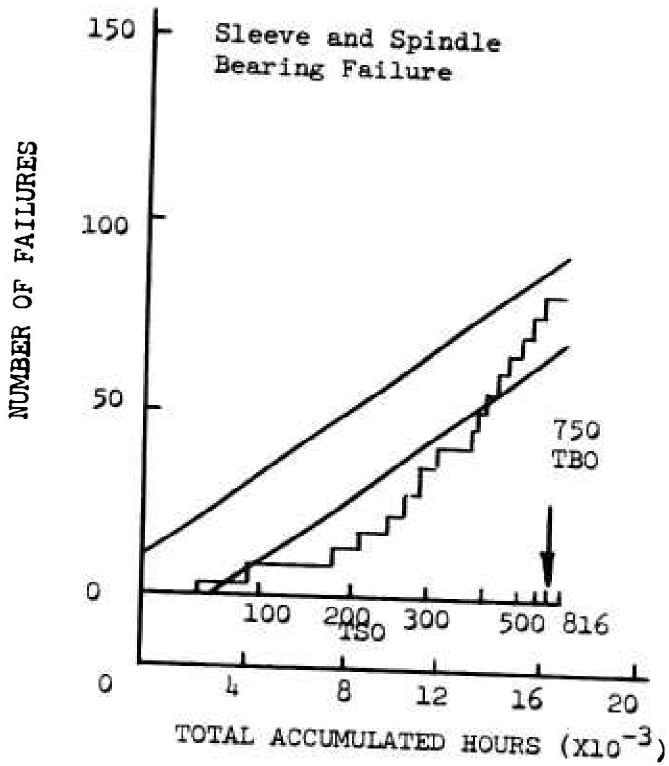


Figure 111. Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head.

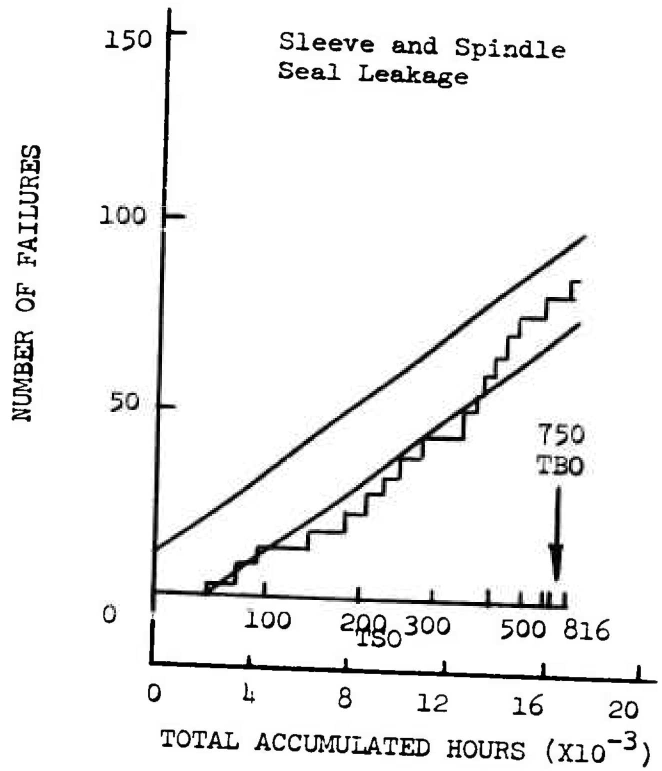


Figure 112. Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head.

(5) Undefined miscellaneous modes

The "undefined leakage" mode was included with "sleeve and spindle seal leakage" and plotted as shown in Figure 114. This mode accentuates the wearout phenomenon of the "sleeve and spindle seal leakage". The remaining failure modes were plotted as shown in Figures 115 through 118. They also exhibit wearout characteristics.

Every distinguishable failure mode of the tail rotor head exhibits wearout prior to the TBO of 750 hours. There is, however, no sharp increase in the failure rate, but rather a gradual, continuous increase. There is, therefore, no obvious point at which a scheduled overhaul would be economically feasible.

The failure rate (Figure 119) and the survival plot (Figure 120) reflect that 11 percent of the rotor heads presently survive to the existing TBO (750 hours). With the indication of an increasing failure rate, it is reasonably projected that the probability of survival would drop off sharply beyond the existing TBO. As the probability of survival approaches zero, we have very few rotor heads removed for a scheduled overhaul; hence, our policy becomes, in fact, that of an "on-condition" philosophy. An extension of the TBO beyond 750 hours would therefore reap diminishing economic benefits.

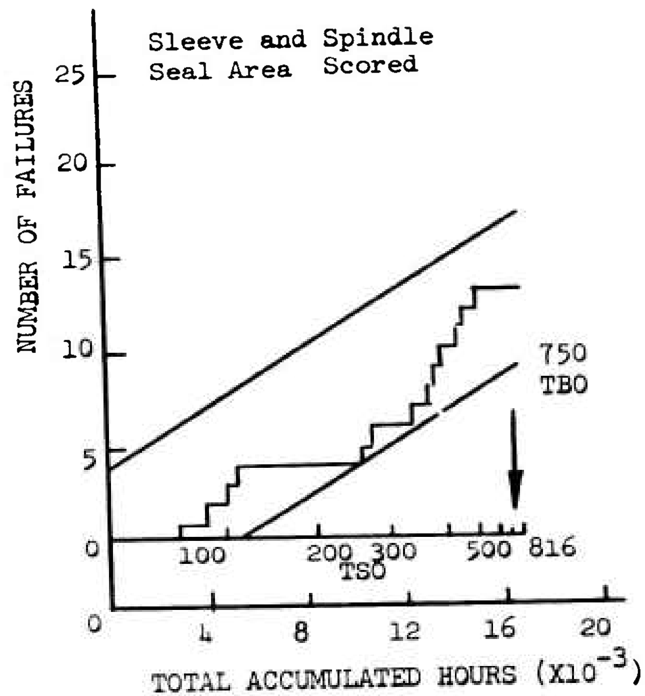


Figure 113. Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head.

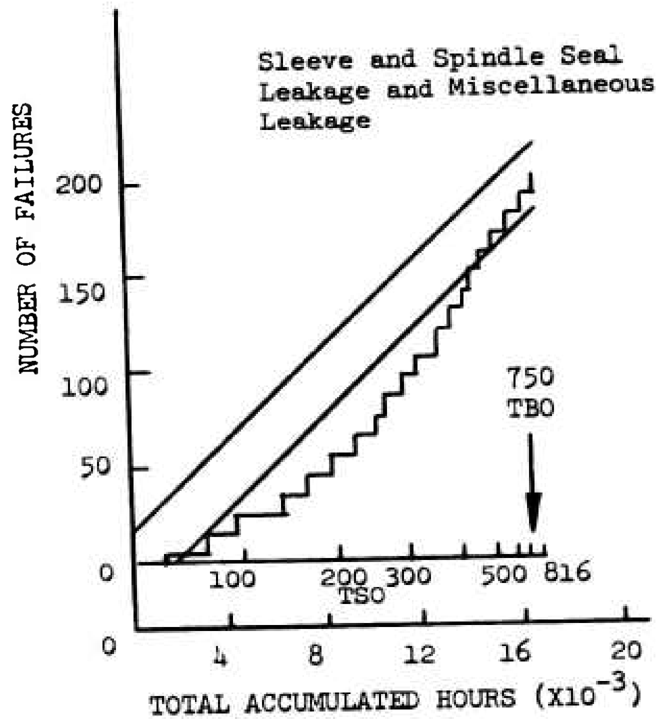


Figure 114. Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head.

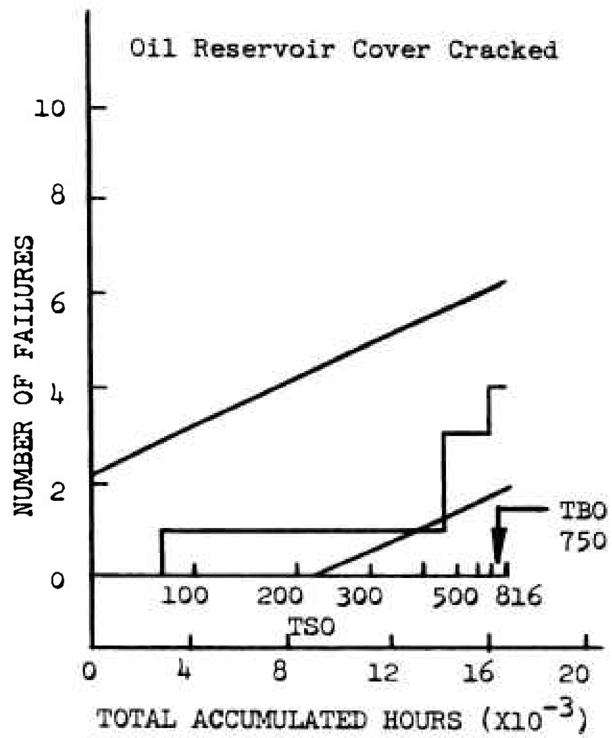


Figure 115. Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head.

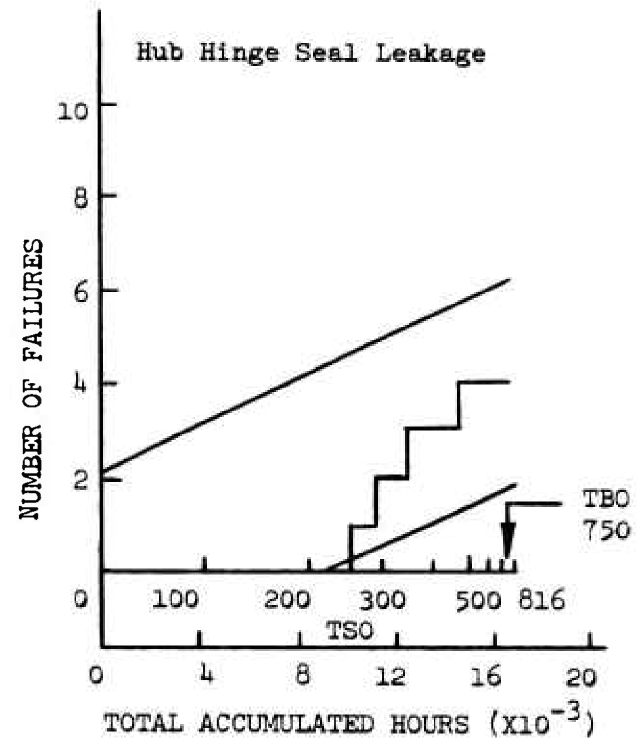


Figure 116. **Failure Versus TSO: CH-3C/HH-3E Tail Rotor Head.**

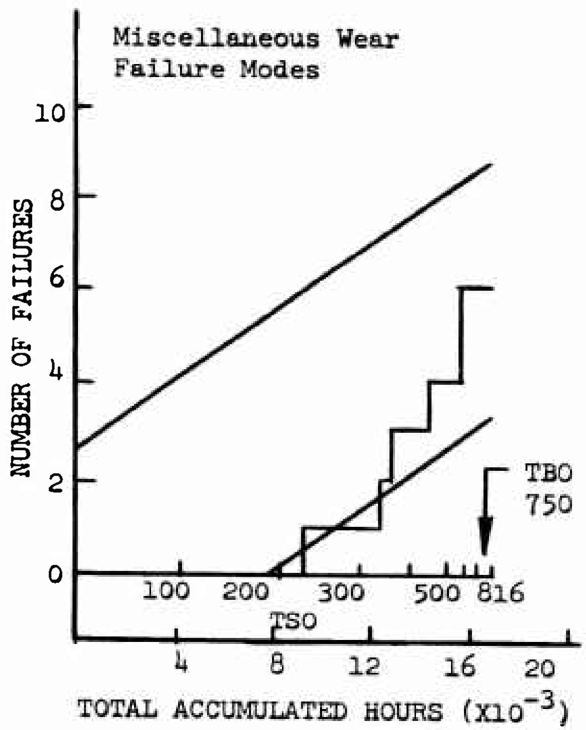


Figure 117. Failure Versus TSO:
CH-3C/HH-3E
Tail Rotor Head.

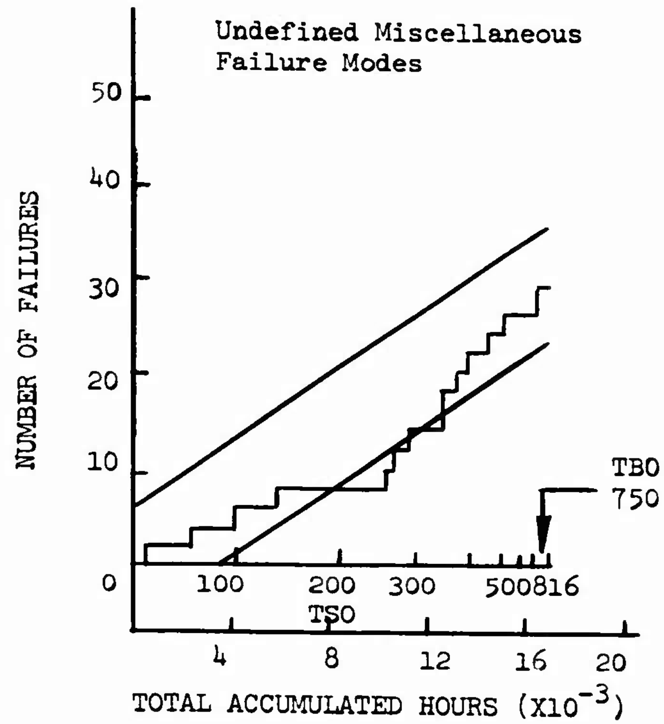


Figure 118. Failure Versus TSO:
CH-3C/HH-3E
Tail Rotor Head.

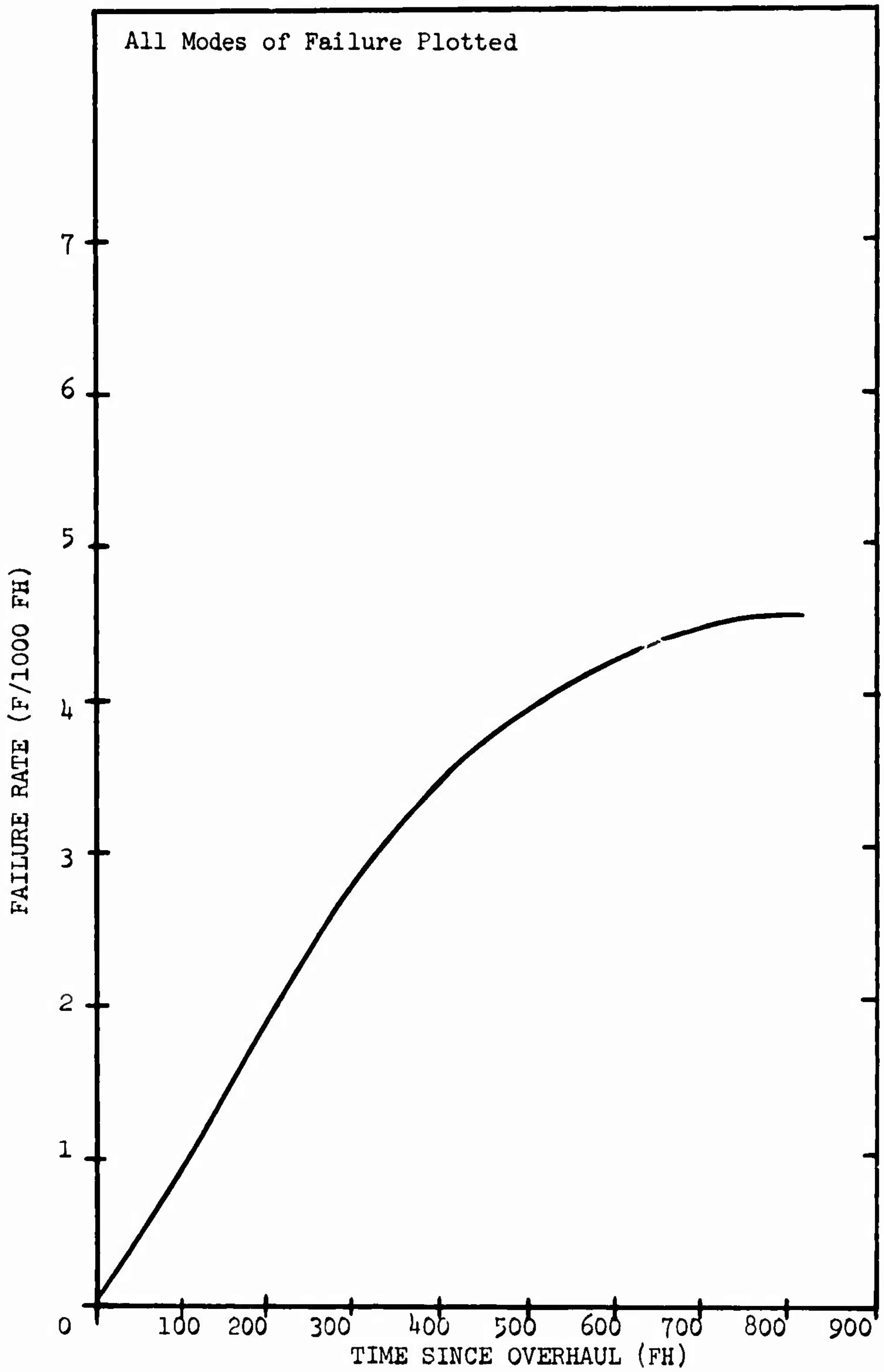


Figure 119. FRAP Failure Rate Plot: CH-3C/HH-3E Tail Rotor Head.

APPENDIX III

H-3 DEVELOPMENT PROGRAM, FAILURE SUMMARY

The failure experienced on the transmission and rotor system components during the H-3 aircraft development program are summarized in Table XIX. These malfunctions are presented by component and indicate the type and level of testing during which they occurred.

TABLE XIX. H-3 DEVELOPMENT PROGRAM FAILURE SUMMARY

				Failure Detected			
Component	Name of Part	Failure Mode	Time To Failure (hours)	Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	High-Speed Sleeve Bearings				X		
	Freewheel Shaft Aft Roller Bearing	Spalling outer race	95		X		
	Planetary Pinion Bearing	Spalling inner race	200		X		
	Freewheel Unit Rollers	Excessive wear			X		
	Freewheel Unit Roller Retainer	Excessive wear			X		
	#1 Side	Excessive wear on spline on cam			X		
	#2 Side	Excessive wear on spline on cam			X		
	Sleeve Bearing	Flaking of overlay material			X		
	Mounting Lug I.G.B.	Minute crack	20		X		
	Freewheel Unit Solenoid Lock	Failed	23		X		
	Idler Shaft	Quill shaft failed	305.5		X		

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	Safety Screws	Stripped	9		X		
	#2 Freewheel Unit	Safety wire & Shur-lok tang broke off	56.8		X		
	Bevel Timken Bearing Cup	Spalled	179.8		X		
	#2 Freewheel Unit	Star washer cracked	179.8		X		
	#2 Freewheel Unit	Star washer cracked	158.3				
	Bushing in Freewheel Unit	Spin & wear on LC-032C-11 Splines	158.3		X		
	Rotor Brake Bracket	Cracked	624		X		
	Planetary Pinion Bracket	Spalled	279.8		X		
	Planetary Sun Gear	Pits on gear face	279.8		X		
	Main Shaft & Planetary Assy.	Snap ring not installed properly causes sun gear to interfere with plate	303		X		

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Failure Detected: Tiedown	Failure Detected: PSTB	Failure Detected: Whirl
Main Gearbox	Bearing Input Gear	Overheating due to no-lube	333.8		X		
	Main Bevel Gear	Fracture of two teeth	451.5		X		
	Main Shaft Duplex Thrust Bearing	Spalling on ball and race	990		X		
	Ring Gear	Broken gear teeth	5.3	X			
	Right Aft Sleeve Bearing	Flaking of flash lead plate		X			
	L/H Fwd. & Aft Input Sleeve Brgs	Failure of gearbox	70	X			
	Aft Freewheel Shaft Bearings	Spalled (2)	165	X			
	Aft Freewheel Shaft Bearings	Spalled (1) for 120°	170.5	X			
	Planetary Pinion Bearings	Spalled 3-inch long (1) Pit on race (1)	170.5	X			
	Planetary Pinion Bearings	Spalled 3-inch long (1) Pit on race (1)	217.3	X			
	Lube Oil Cooler	Failed due to misalignment	252	X			

TABLE XIX -Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	Herringbone Gear	Fracture	323.3	X			
	L/H FWD Sleeve Bearing	Overlay of lead flaked	333.3	X			
	Shaft Test Stand	Excessive fretting	351.8	X			
	Herringbone Gear	Fracture	374.3	X			
	Planetary Brgs.	Spalled (3 of 5)	240	X			
	Planetary Roller Bearings	Spalled (3 of 5)	70	X			
	Roller Bearing Freewheel	Spalled (2 of 2)	70	X			
	Cam Shaft	Failed	70	X			
	Roller Bearing-Upper Main Shaft	Spalled for 90°	70	X			
	Roller Bearing-Freewheel	Spalled (1 of 2)	70	X			
	Planetary Roller Bearing	Spalled (2 of 5)	170.5	X			

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Ticdown	PSTB	Whirl
Main Gearbox	Upper Main Shaft Roller Bearing	Spalled for 30°	170.5	X			
	Lower Main Shaft Ball Bearing	Outer race - fatigue pit 1/8 inch diameter	170.5	X			
	Lockout Assy. Freewheel Unit	Splines excessively worn	170.5	X			
	Upper Main Shaft Roller Bearing	Spalled outer race	170.5	X			
	Lockout Assy. Freewheel Unit	Splines excessively worn	323.3	X			
	Metal Oil Shields	Cracked at supports	333.8	X			
	Shaft	Attach flange cracked	250	X			
	Shaft	Spline tooth cracked	250	X			
	Herringbone Gear	Chipped	44			X	
	#2 Freewheel Sleeve Bearing	Failed	87.6			X	
	#1 Side Freewheel Unit	Rollers & housing overheated	101.5			X	

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	Sun Cear	Interference	44			X	
	Input Assemblies	Excessive working of splines	44			X	
	Herringbone Gear	Excessive working of splines	44			X	
	Outer Shaft Roller Bearings	Spinning nut torque loss	44			X	
	Throughshaft Splines	Excessive fretting	44			X	
	Herringbone Gear	No failure	27.9			X	
	Cam	Indentation of cam face	28.9			X	
	Housing	Indentation of roller raceway	28.9			X	
	Rollers	Indented	28.9			X	
	Lugs	Pins broken off	28.9			X	
	Input Shaft	Excessive spline wear	27.9			X	
	Nylon Ring	Broken in many pieces	28.9			X	
	Sleeve Bearing	Failed	43.6			X	

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	Input Seal	Excessive leakage	17.8			X	
	Input Seal	Excessive leakage	3			X	
	R/H Fwd & Aft Sleeve Bearing	Flaking on both, cavitation on one	116.2	X			
	Lower Main Shaft Thrust Bearing	Improper installation	115	X			
	Input Bevel Pinion Gear	Excessive scuffing	174.5	X			
	Mair Bevel Gear	Excessive scuffing	424.5	X			
	Timken Input Pinion Bearing	Pit in inner race	400	X			
	Planetary Pinion Bearing	Spalled inner race		X			
	Planetary Pinion Gear	Spalled on race	400	X			
	Generator Free-wheel Retainer	Work lugs	914.8	X			

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbcx	Input Bevel Pinion	Fractured tooth & badly scuffed	257.5	X			
	Main Bevel Gear	Badly scuffed	507.5	X			
	Planetary Pinion Bearings	Spalled inner race	107.5	X			
	Sleeve Bearing	Medium to heavy tracking	257.5	X			
	Input Pinion Bearing	Badly spalled cup	107.5	X			
	L/H Helical Gear	Fractured gear teeth	396.3	X			
	Input Helical Gear	Damaged teeth	646.3	X			
	R/H Fwd. Sleeve Bearing	Melted overlay	138.8	X			
	L/H Fwd. Sleeve Bearing	Erosion & samll pit	138.8	X			
	L/H Fwd. Aft Bearing	Contaminated	396.3	X			
	Main Bevel Gear	Fractured tooth & scuff	172.5	X			

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Failure Detected: Tiedown	Failure Detected: PSTB	Failure Detected: Whirl
Main Gearbox	Helical Gear	2 fractured teeth & heavy end loading	33.8	X			
	Sleeve Bearings	Erosion, tracking, & melting of overlay	172.5	X			
	Planetary Gear	Fractured gear tooth	894.5	X			
	Sleeve Bearings	Tracking & erosion	684	X			
	Main Bevel Gear	Fractured tooth	257.3	X			
	Top Housing	Cracked near two mounting holes	957.3	X			
	Main Shaft Lower Thrust Bearing	Spalled	1389.3	X			
	Gear Shaft Input	Cracked	1354	X			
	Bevel Output Gear	Fractured tooth	25.5	X			
	Bevel Output Gear	Cracked tooth	25.5	X			
	Outer Shaft	Fractured segment	48.3	X			
	Second-Stage Spur Gear	Fractured tooth	236.5	X			

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	TTO Roller Bearing	Spalled	300	X			
	TTO Roller Bearing	Spalled	300	X			
	Top Housing	Hairline cracks 3 bolts holes	326.5	X			
	Outer Shaft Roller Bearing	Seized roller cage	108	X			
	Bevel Pinion	Fractured one tooth	239.2	X			
	Outer Shaft Roller Bearing	Spalled condition	466.6	X			
	TTO Bearing	Spalled outer race	102.5	X			
	Outer Shaft Roller Bearing	Spalled outer race	102.5	X			
	Main Bevel Gear	Excessive scuffing	108	X			
	Main Bevel Gear	Excessive scuffing	108	X			
	TTO Timken Brg.	Fractured cage & spalled races	340.3	X			
	TTO Timken Brg.	Spalled races & rollers	564.6	X			
	Planetary Pinion	Damaged	210.5	X			

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	Outer Shaft Bearing	Damaged	210.5	X			
	Outer Shaft	Damaged	210.5	X			
	Bearing Retainer	Damaged	210.5	X			
	Planetary Pinion	Fractured several teeth	254.3	X			
	Output Bevel Gear	Fractured 4 teeth	29.8	X			
	Output Bevel Gear	Fractured 2 teeth	34.8	X			
	Output Bevel Gear	Fractured 1 tooth	30	X			
	Planetary Pinions	Fractured teeth	176.3	X			
	Intermediate Shaft	Fracture of lower brg. retainer	186.3	X			
	Outer Shaft Roller Bearing	Failed	186.3	X			
	R/H Second-Stage Spur Gear	Fractured segment of tooth	29.8	X			
	Output Bevel Gear	Fractured 2 teeth	57	X			
	Output Bevel Gear	Fractured 2 teeth	45.3	X			

TABLE XIX- Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Tiedown	PSTB	Whirl
Main Gearbox	Input Sleeve Bearing (#2)	Lacking lubrication during starts & high power acceleration at low rpm	29.5		X		
	Input Sleeve Bearing (#1 side)	Failed	141.3		X		
	Planetary Pinion Bearing	Spalling	199		X		
	Freewheel Unit (#1 side)	Excessive wear at ends of rollers	199		X		
	Planetary Pinion	Fractured several teeth	132.3	X			
	Planetary Pinion	Fractured 3 teeth	156.6	X			
	Ring Gear	Fractured several teeth	176.3	X			
	Input Bevel Gear	Tooth fracture & moderate spalling	244.5	X			
Tail Gearbox	Output Shaft Brg.	Overheating	206				X
	Center Housing	Cracked attachment lub	734.3				X
	Input Bevel Gear	Deep pitting below pitchline	1340				X

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Failure Detected: Tiedown	Failure Detected: PSTB	Failure Detected: Whirl
Tail Gearbox	Hub Flapping Bearing	Fretting & brinneling	1004				X
	Trunnion Bearing	Excessive wear	231				X
Main Rotor Head	Vertical Hinge Grease Seal	Cut & distorted	44		X		
	Blade Lock Piston	Cracked longitudinal - (one end)				X	
	Seal Retainer	EC1357 cement not satisfactorily bonded	6		X		
	Stack Bearing	Moisture corrosion slight, brinneling & fretting	44		X		
	Stack Bearing	Moisture corrosion slight, brinneling & fretting	44		X		
	Seal Retainer	EC1357 cement not satisfactorily bonded	44		X		
	Socket	Out of plane	44		X		
	Thrust Washer	Dished & gouged from bolts	44		X		

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Failure Detected: PSTB	Failure Detected: Tiedown	Failure Detected: Whirl
Main Rotor Head	Flapping Hinge Brgs	Skewing & brinnel of inner & outer races-spalling & cracked	184.3				X
	Damper Cylinder	Cracked from port to center of bracket attachment lug	184.3				X
	Droop Stop Spring	Failure caused by interference with antiflapping spring					X
	Bracket (in anti-flap assy.)	Binding provides no positive stop antiflapping arm					X
	Damper	Cracking	80				X
	Draw Bar	Cracking					X
	Spindle Assy. (5 sets)	Chafing-Ears Scoring-Ears	500 500				X
	Spindle Assy. (5 sets)	Chafing-Ears Scoring-ears	500 500				X
	Stack Bearings (5 sets)	Nylon ball cage popped out & allowed balls to rub	500				X
	Sleeve & Spindle Assy. (oil)	Seal leaked $1\frac{1}{2}$ - 2 oz. of oil per 4 hours					X

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Failure Detected: PSTB	Failure Detected: Tiedown	Failure Detected: Whirl
Main Rotor Head	Antiflapping Re-strainer Draw Bar	Fracture					X
	Damper Trunnions (Fabroidtype)	Excessive play 0.011 inch	500				X
	Damper Trunnions Bearings	Outer shoulder cracked in several places by skew ball	500				X
	Damper Cylinders	Cracked in mounting area caused by improper stress relief	1224.0				X
	Shaft "O" Rings (Damper)	Wear caused loss of oil	658				X
	Spindle	Small crack at blade fold pressure inlet	1000				X
	Vertical Hinge Seal	Leakage oil	113.5				X
	Antiflapping Re-strainer Draw Bar	Fracture					X
	Damper Cylinder	Fracture of mounting lub	285.3				X
	Flapping Hinge Brg. & Inner Race	Severe spalling & fracture	158.7				X

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Failure Detected: PSTB	Failure Detected: Tiedown	Failure Detected: Whirl
Main Rotor Head	Flapping Hinge Bearing	Spalled inner race	175				X
	Anticoning Assembly	Spring assy. failed (several)	30			X	
	Damper Cylinder	Cracked (pin hole to bore)	1181.3			X	
Tail Rotor Head	Flapping Bearing	Excessive wear	432.2				X
	Trunnion Bearing	Extreme wear	259.8				X
	Hub Bearing Inner Race	Fretting & brinneling	740				X
	Tail Rotor Hub	Worn splines	819.6				X
	Tail Rotor Gearbox Output Shaft	Worn splines	55.6				X
	Tail Rotor Hub	Worn splines	201				X
	Tail Rotor Gearbox Output Shaft	Worn splines	201				X
	Flapping Bearing	Some fretting & needle skewing			X		
	Tail Rotor Trunnion Bearing	Excessive play - false brinneling	349.5		X		

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected			
				Regen Bench	Tiedown	PSTB	Whirl
Tail Rotor Head	Washer	Worn through (3)	200				X
	Spindle	Cracked flapping pin hole	200				X
	Flapping Hinge Brg. Inner Race	Spalled on end loading	1376		X		
Main Rotor Blade	Tip Cap	Cracking	246.3				X
	Bolt Balance Weight	Fracture	992.5				X
	Blade Tip	Developed small crack	75.3		X		
	Tip Caps	Cracks			X		
	Inner Race Upper Main Bearing	Spalling	247.5		X		
	Inner Race Plan. Pinion Prg.	Spalling	43.5		X		
	#2 Fwd. Sleeve Bearing	Bearing plating flaked on an area of inner diameter			X		

TABLE XIX - Continued

Component	Name of Part	Failure Mode	Time To Failure (hours)	Failure Detected: Regen Bench	Failure Detected: Tiedown	Failure Detected: PSTB	Failure Detected: Whirl
Main Rotor Blade	Planetary Pinion Bearing	Slight spalling	292.5		X		
	#4 Sleeve Brg.	Flashed overlay on I.D,	292.5		X		
	Main Bevel Pinion Gear	Fractured heel section of 1 tooth	386.3		X		
Tail Rotor Blade	Blade	Fracture	256				X
	Blade	Pocket skin unbonded from honeycomb	28.5				X
	Blade	Honeycomb & skin pocket separated from spar	664		X		
	Blade	Bond separation at train edge	522.3		X		
Tail Drive Shaft	Shaft Thrust Brg. Bushing	Unfolding pylon quick-disconnect jams not indexed caused slipping			X		